Effective Use of Virtual and Augmented Reality – A Technical and Socio-Behavioral Affordance Perspective

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Jennifer Fromm
aus
Remscheid

1. Gutachter: Prof. Dr. Stefan Stieglitz
2. Gutachter: Prof. Dr. Oliver Büttner

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Abbreviations

IT	Information technology
IS	Information Systems
VR	Virtual reality
AR	Augmented reality

Abstract (German)

Virtual und Augmented Reality gewinnen als Schlüsseltechnologien für das Metaverse zunehmend an Relevanz. Trotz ihrer Bedeutung für das Metaverse werden Virtual und Augmented Reality noch nicht in großem Umfang genutzt. Neben technischen Limitationen könnte ein Mangel an effektiver Nutzung ein Grund dafür sein. In der Information-Systems-Disziplin versteht man unter effektiver Nutzung die erfolgreiche Realisierung der Handlungspotenziale einer Technologie, auch als Affordances bezeichnet. Im Rahmen dieser kumulativen Dissertation wurde untersucht, wie die effektive Nutzung von Virtual und Augmented Reality aus einer technischen und einer sozio-behavioralen Affordance-Perspektive gefördert werden kann. Aus einer technischen Affordance-Perspektive wurde untersucht, wie Virtual- und Augmented-Reality-Systeme gestaltet werden sollten, um ihren effektiven Einsatz in den Kontexten der Hochschullehre und des Krisenmanagements zu ermöglichen. Die Ergebnisse zeigen, dass sich eine effektive Nutzung durch die Implementierung von Designelementen fördern lässt, die die Wahrnehmung der einzigartigen Affordances von Virtual und Augmented Reality im Vergleich zu bestehenden Systemen ermöglichen. Aus einer sozio-behavioralen Perspektive wurde untersucht, welches Nutzer:innenverhalten die effektive Nutzung von sozialen (Virtual-Reality-)Anwendungen ausmacht, bei denen die Nutzer:innen auf derselben Plattform gemeinsame oder unterschiedliche Ziele verfolgen. Die Ergebnisse zeigen, dass effektives Nutzungsverhalten nicht nur die erfolgreiche Realisierung von Affordances beinhaltet, sondern auch den Umgang mit Einschränkungen, die sich aus technischen Limitationen und Interaktionen mit anderen Nutzer:innen ergeben, die unterschiedliche Ziele verfolgen. Die Dissertation liefert einen theoretischen Mehrwert zur Information-Systems-Forschung durch präskriptives Wissen in Form von Gestaltungsprinzipien und einem besseren Verständnis des Nutzer:innenverhaltens, das die effektive Nutzung von Virtual und Augmented Reality ausmacht.

Abstract (English)

The relevance of virtual and augmented reality as enabling technologies of the metaverse is increasing. Despite their importance for the metaverse, both virtual and augmented reality are not yet widely used. Besides technical limitations, a lack of effective use could be a reason for this. In the field of Information Systems, effective use is understood as the successful realization of a technology's potentials for action, or so-called affordances. This cumulative dissertation examined how the effective use of virtual and augmented reality can be promoted from a technical and socio-behavioral affordance perspective. From a technical affordance perspective, it was investigated how virtual and augmented reality systems should be designed to enable their effective use in the contexts of higher education and emergency management. The results show that effective use can be fostered by implementing design elements that promote the perception of the unique affordances of virtual and augmented reality compared with existing systems. From a socio-behavioral perspective, it was examined what user behavior constitutes the effective use of social (virtual reality) applications in which users pursue shared versus different goals on the same platform. The findings reveal that effective use behavior involves not only the successful realization of affordances, but also dealing with constraints emerging from technical limitations and interactions with other users pursuing different goals. The dissertation contributes prescriptive knowledge in the form of design principles and a better understanding of the user behavior that constitutes the effective use of virtual and augmented reality to Information Systems research.

1 Introduction

1.1 Research context and motivation

With recent technological advances and immense investments from large companies, such as Meta and Microsoft, the relevance of virtual and augmented reality (VR / AR) as enabling technologies of the metaverse is increasing (Mystakidis, 2022; Park & Kim, 2022). The metaverse refers to a web of immersive virtual worlds in which users are represented as avatars and can engage in diverse activities, such as social networking, gaming, shopping, learning, and working (Dolata & Schwabe, 2023). VR allows users to be fully immersed in virtual worlds, while AR provides an extension of the physical world with digital objects (Milgram & Kishino, 1994). While the metaverse is still more of a future vision, VR and AR are already being experimented with in a variety of application areas, such as gaming, entertainment, education, training, manufacturing, marketing, and remote work (Liberatore & Wagner, 2021; Wohlgenannt et al., 2020). Nevertheless, the widespread use of VR and AR is still far from being achieved despite decades of research and corporate initiatives (Steffen et al., 2019).

In addition to the still existing technical limitations, one explanation could be a lack of *effective use*, that is, the kind of use that contributes to the achievement of user goals (Burton-Jones & Grange, 2013). Effective use can be achieved by successfully realizing the action potentials of technologies, or so-called *affordances* (Burton-Jones & Volkoff, 2017). Affordances are goal-oriented action possibilities that emerge from the relationship between the user and technology (Markus & Silver, 2008). This means that the material properties of technologies enable and limit a set of action possibilities, but at the same time, the perception of affordances varies among different users depending on their goals (Strong et al., 2014). VR and AR enable distinctive affordances, such as depicting the non-existent, overcoming space-time linearity, and enhancing the physical world with additional information (Steffen et al., 2019). The overarching goal of this doctoral thesis is to understand how the effective use of VR and AR can be fostered from both a technical and socio-behavioral affordance perspective (Mesgari et al., 2023).

1.2 Research questions and objectives

The first research question examines how to *design* VR and AR systems in a way that helps users achieve their goals, or in other words, to use them effectively. Previous research has suggested that designers can facilitate the perception of relevant affordances for the achievement of user goals (Grgecic et al., 2015; Mesgari et al., 2023; Norman, 1988). The studies associated with the first research question contribute prescriptive knowledge in the form of design principles (Jones & Gregor, 2008). These focus on how to design for the effective use of VR in higher education and AR in emergency control rooms. There already exist many design-oriented studies on VR in the context of education (e.g., Al-Gindy et al., 2020; Ding et al., 2020; Hernández-Chávez et al., 2021) and AR in the context of emergency management (e.g., Brandao & Pinho, 2017; Brunetti et al., 2015; Luchetti et al., 2017; Nunes et al., 2019). However, the design is typically informed solely by the technical possibilities provided by VR and AR, while the user goals are neglected. The studies in this doctoral thesis provide a distinctive contribution by proposing design principles based on a design process that takes into account both the unique affordances provided by VR/AR and user goals. Thus, the first research question is as follows:

RQ1: *How should VR and AR systems be designed to foster their effective use in the contexts of higher education and emergency management?*

The second research question examines the *user behavior* that constitutes an effective use of social (VR) applications. The key to effective use is the successful realization of action potentials, which is also termed affordance actualization in the IS literature (Burton-Jones & Volkoff, 2017; Strong et al., 2014). Previous research has already identified relevant affordances to be actualized in order to achieve user goals in different contexts (e.g., Jayarathna et al., 2020; Tim et al., 2018; Zeng et al., 2020). Furthermore, it has been proposed that the actualization outcomes of individual users contribute in sum to the achievement of overarching organizational goals (Burton-Jones & Volkoff, 2017; Strong et al., 2014; Karlsen et al., 2019). However, social (VR) applications invite users with different, sometimes even opposing, goals to use the same platform. If the social influence of other users is neglected, a lack of goal achievement will most likely be attributed to technical constraints (e.g., feature limitations), user characteristics (e.g., lack of IT knowledge), or the organizational context (e.g., organizational culture), rendering an incomplete picture of effective use. Thus, IS researchers have emphasized the need to investigate the influence of other actors on the successful actualization of affordances, or effective use, respectively (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Sæbø et al., 2020). In this regard, a study has indicated that other users might encourage the actualization of further affordances, allowing for the achievement of higher-level goals (Abouzahra & Ghasemaghaei, 2022). Extending this line of research, the studies associated with the second research question focus on the effective use of social VR apps in higher education where students work together toward *shared goals*. Another study explores the effective use of social media for collective action as a contrasting context in which organizations pursue *different goals* using the same platform. This allows to answer the following second research question:

RQ2: *What constitutes the effective use of social (VR) applications in which users pursue shared goals versus different goals on the same platform?*

1.3 Thesis structure and list of publications

This doctoral thesis is a cumulative dissertation that follows the regulations governing doctoral proceedings at the Faculty of Engineering at the University of Duisburg-Essen. The thesis consists of a synopsis of the results and a series of peer-reviewed research articles published in international journals and conference proceedings.

Section 2 summarizes the research background regarding the effective use of VR and AR. This chapter defines important terms, explains the relationship between the affordance concept and effective use, and presents previous research related to the thesis topic. Section 3 outlines the research strategy and methods that were applied in the studies described in this thesis. Section 4 shows how the results of the individual research articles included in this thesis build on each other. Section 5 discusses the findings in relation to previous research and the research questions. Section 6 provides a conclusion and reflects on the theoretical contributions, practical implications, limitations, and future research opportunities.

Table 1 provides an overview of the included papers in logical order. This does not necessarily correspond to chronological order because of the different turnaround times of journals and conference proceedings. The table shows the titles, authors, years, publication types (CNF = Conference, JNL = Journal), and publication outlets of the research articles. For each paper, rankings, impact factors, and citation counts are provided. This includes the VHB-JOURQUAL3 ranking[1], the Journal Impact Factor (JIF), and citation counts from Google Scholar[2]. Seven research articles were included in this thesis. The papers were co-authored with researchers from the University of Duisburg-Essen (Germany), the University of Potsdam (Germany), Paderborn University (Germany), the University of Liechtenstein (Liechtenstein), and the University of Agder (Norway).

Of the seven articles, five articles were either published or under review in journals, namely Computers & Education, The Internet and Higher Education, Information Systems Frontiers, The DATA BASE for Advances in Information Systems, and European Journal of Information Systems. The latter belongs to the Senior Scholars' Basket of Journals, which includes eleven journals selected by the Association for Information Systems. Furthermore, The DATA BASE for Advances in Information Systems has a B-ranking according to the VHB ranking of publication outlets. With more than 1,000 citations, the

[1] https://vhbonline.org/vhb4you/vhb-jourqual/vhb-jourqual-3/, last access 2023-07-25
[2] https://scholar.google.com/, last access 2023-07-25

article published in Computers & Education received a particularly high number of citations. Two articles were published in conference proceedings, of which one was a full paper (Internationale Tagung Wirtschaftsinformatik) and one article was a research-in-progress paper (European Conference on Information Systems).

Table 1. *List of publications*

#	Publication		Type	VHB JQ3	Impact Factor	Citations (Google Scholar)
1	Title:	A Systematic Review of Immersive Virtual Reality Applications for Higher Education: Design Elements, Lessons Learned, and Research Agenda	JNL	-	12.0 (2022)	1419
	Authors:	Radianti, J., Majchrzak, T. A., **Fromm, J.**, & Wohlgenannt, I.				
	Year:	2020				
	Outlet:	Computers & Education				
2	Title:	More than Experience? - On the Unique Opportunities of Virtual Reality to Afford a Holistic Experiential Learning Cycle	JNL	-	8.6 (2022)	90
	Authors:	**Fromm, J.**, Radianti, J., Wehking, C., Stieglitz, S., Majchrzak, T. A., & Vom Brocke, J.				
	Year:	2021				
	Outlet:	The Internet and Higher Education				
3	Title:	Social Media Data in an Augmented Reality System for Situation Awareness Support in Emergency Control Rooms	JNL	B	5.9 (2022)	16
	Authors:	**Fromm, J.**, Eyilmez, K., Baßfeld, M., Majchrzak, T. A., & Stieglitz, S.				
	Year:	2021				
	Outlet:	Information Systems Frontiers				
4	Title:	A Systematic Review of Empirical Affordance Studies: Recommendations for Affordance Research in Information Systems	CNF (Short paper)	B	-	22
	Authors:	**Fromm, J.**, Mirbabaie, M., & Stieglitz, S.				
	Year:	2020				
	Outlet:	European Conference on Information Systems				
5	Title:	Virtual Reality in Digital Education: An Affordance Network Perspective on Effective Use Behavior	JNL	B	2.8 (2022)	-

	Authors:	**Fromm, J.**, Stieglitz, S., & Mirbabaie, M.				
	Year:	2023				
	Outlet:	The DATA BASE for Advances in Information Systems				
6	Title:	The Effects of Virtual Reality Affordances and Constraints on Negative Group Effects during Brainstorming Sessions	CNF (Full paper)	C	-	18
	Authors:	**Fromm, J.**, Mirbabaie, M., & Stieglitz, S.				
	Year:	2020				
	Outlet:	Internationale Tagung Wirtschaftsinformatik				
7	Title:	Paradoxical Tensions Between Social Media Affordances and Constraints for Collective Action – Analysing the Interplay of Organisations Pursuing Different Environmental Policy Goals	JNL (Third revision round)	A	9.5 (2022)	-
	Authors:	Stieglitz, S., **Fromm, J.**, & Mirbabaie, M.				
	Year:	2023				
	Outlet:	European Journal of Information Systems				

2 Background

2.1 VR and AR as enabling technologies of the metaverse

With Facebook's rebranding to Meta in October 2021, VR and AR received increasing attention as technologies enabling the metaverse (Mystakidis, 2022). It is difficult to provide a clear definition at the present time because many actors are trying to shape the vision of the metaverse (e.g., big tech companies, non-commercial providers, and game producers), and therefore there are conflicting views about the term's meaning (Dolata & Schwabe, 2023). A meta-synthesis of existing definitions concluded that the metaverse is *"an interconnected web of ubiquitous virtual worlds partly overlapping with and enhancing the physical world. These virtual worlds enable users who are represented by avatars to connect and interact with each other, and to experience and consume user-generated content in an immersive, scalable, synchronous, and persistent environment. An economic system provides incentives for contributing to the Metaverse"* (Weinberger, 2022). The metaverse enables users to do *"practically anything"*, be it participating in events, socializing, trading virtual goods, playing games, or working (Dolata & Schwabe, 2023). VR and AR are important building blocks of the metaverse, enabling the representation of users through avatars and an immersive experience; however, the creation of the metaverse also requires other technologies, such as blockchains, enabling the secure exchange of virtual goods (Park & Kim, 2022).

VR is defined as an *"immersive technology to simulate interactive virtual environments or virtual worlds with which users become subjectively involved and in which they feel physically present"* (Wohlgenannt et al., 2020 p. 457). The technology is associated with particularly high levels of immersion, presence, and interactivity (Mütterlein, 2018). Immersion can be seen either as an objective property of VR systems or as a subjective experience (Nilsson et al., 2016). From an objective property perspective, the degree of immersion depends on how many sensory modalities a VR system appeals to, how natural the interaction with the system feels, and the extent to which physical reality is blocked out (Slater, 2018). From a subjective experience perspective, immersion refers to *"the experience of being surrounded by the virtual environment that increases proportionally with the number of modalities provided with artificial stimuli"* (McMahan, 2003). In VR research, the views are seen as complementary; for instance, Agrewal et al. (2020) proposed that the technological attributes of a VR system can facilitate the subjective experience of immersion. Presence describes the sensory illusion that one is physically located in the virtual environment and together with other potential users, even though one is cognitively aware that this is not the case (Felton & Jackson, 2022; Slater, 2018). Interactivity *"refers to the degree to which users of a medium can influence the form or content* *of the mediated environment"* (Steuer, 1992, p. 80). Together, presence and interactivity contribute to an immersive experience (Mütterlein, 2018). While VR aims to fully immerse the user in a virtual world, AR can be understood as a form of mixed reality *"in which an otherwise real environment is 'augmented' by means of virtual (computer graphic) objects"* (Milgram & Kishino, 1994, p. 4).

The unique characteristics of VR make the technology most suitable for reducing physical risk, reducing resource costs, enabling physically incapable participants, depicting the non-existent, and overcoming space-time linearity (Steffen et al., 2019). For example, in the context of education, students can learn surgical procedures in a safe environment, meet in collaborative learning spaces independent of their location, and visit physically unreachable places like the crater of an active volcano (Radianti et al., 2020). VR can improve knowledge gain, knowledge retention, engagement with learning topics, and learning motivation (e.g., Fromm, Radianti, et al., 2021; Hamilton et al., 2021; T. A. Majchrzak et al., 2022; Pande et al., 2021). AR, on the other hand, is considered most useful in contexts in which the presentation of additional information alongside the physical world can increase task success (Steffen et al., 2019). This is, for example, the case in the context of emergency management, in which emergency forces still need to take in information from the physical world, while they could also benefit from the integration of additional information sources, such as social media (Brunetti et al., 2015; Fromm, Eyilmez, et al., 2021; Luchetti et al., 2017; Nunes et al., 2019). IS research also emphasized the potential of AR to visualize large amounts of data because AR allows users to view data from different angles as well as tangible and verbal interaction with data (Olshannikova et al., 2015).

Although the use of VR and AR has been associated with several benefits, studies have also shown undesired effects. For example, the use of VR in education can lead to a higher cognitive load, which is why, in some cases, it does not lead to the desired improvement in learning outcomes (di Natale et al., 2020). Similarly, the use of AR in the context of emergency management can result in information overload, which impairs decision-making quality (Fromm, Eyilmez, et al., 2021). Thus, it is important to understand how to design for the effective use of VR and AR systems and how their affordances can be leveraged to achieve user goals.

2.2 The ontological nature of the affordance concept

The affordance concept was developed by ecological psychologist James J. Gibson (1979), who studied how animals (including humans) perceive the action potentials of their environment. He challenged the assumption that animals first evaluate the properties of objects to infer the action potentials of their environment. Instead, he assumed that animals are able to perceive directly *"what it offers (...), what it provides or furnishes, either for good or ill"* (Gibson, 1979, p. 197). Affordances are action potentials that emerge from the relationship between an animal and its environment (Chemero, 2003; Stoffregen, 2003). For example, the physical properties of a chair might enable the perception of a sitting affordance, but only for members of a species that has the habit of sitting (Gibson, 1979).

The concept found its way to other research disciplines, where it was also applied to the study of technology. In the field of human-computer interaction, for example, Norman (1988) suggested that the design of everyday objects influences how easily users perceive the intended use of objects (including IT artifacts). The starting point for the affordance concept's way into the IS field was established when Orlikowski (1992) proposed that humans embed social structures into IT artifacts through design and use, while IT artifacts, in turn, afford and constrain human action, also referred to as the duality of technology. A few years later, DeSanctis and Poole (1994) asserted that both the physical characteristics and what they referred to as the *"spirit"* of IT artifacts afford and constrain human action. The concept of spirit captures the intentions of designers behind the creation of IT artifacts (DeSanctis & Poole, 1994). However, it was perceived as a *"very vague and mystical term"* and was not widely used in IS research (Berente & Recker, 2021). There remained a dearth of appropriate terminology, despite the growing interest in researching the use of IT artifacts, while considering both the materiality of IT artifacts and their human interpretation (Orlikowski, 2007; Orlikowski & Scott, 2008). Markus and Silver (2008) used the concept of affordance to reconceptualize the spirit concept in a manner that IS researchers had a useful vocabulary at their disposal to research technology in use. They defined affordances as *"the possibilities for goal-oriented actions afforded to specified user groups by technical objects"* (Markus & Silver, 2008, p. 622).

Since then, a variety of affordance studies have been published, particularly those related to social media; however, the IS field still lacks a cumulative affordance research tradition (Fromm et al., 2020). For instance, despite the fact that Treem and Leonardi (2013) proposed five social media affordances early on, Hafezieh and Eshraghian (2017) synthesized social media affordances based on a review of 152 studies, and Karahanna et al. (2018) developed a framework that encapsulated all the social media affordances identified to date; studies on social media affordances continue to uncover new ones. Another observable pattern is that new affordances are always identified from scratch with emerging technologies, such as VR and AR (Steffen et al., 2019), blockchain (Du et al., 2019), and big data analytics (Lehrer et al., 2018), rather than looking at the extent to which affordances can be transferred from already well-known technologies.

Even going so far as to refer to the identification of affordances as *"the new formula"* for publications, Berente and Recker (2021) criticized the concept's infrequent application in attempting to explain pertinent IS phenomena. As a result, the affordance notion has become *"the flavor of the month"*, according to Volkoff and Strong (2017, p. 234), who raised the issue that *"anything and everything related to IT artifacts is being labelled an affordance*". The problem of affordances being frequently mistaken for technological features, direct usage of technology, or usage consequences was also brought up by researchers in the IS field (Fromm et al., 2020; Leidner et al., 2018). Few comparisons can be drawn between the findings of different studies because of the ever-increasing number of affordances detected and the ambiguity surrounding what should be classified as an affordance.

Attempts have been made to define the ontological nature of affordances. According to Bernhard et al. (2013), for instance, affordances result from the interaction between an IT artifact's characteristics and user attributes (e.g., goals and levels of ability). Although there is agreement that affordances are relational, IS scholars have different opinions on whether affordances are intentionally built into IT artifacts by designers or emergent in practice (Alshawmar, 2021; Stendal et al., 2016). To acknowledge the numerous understandings of the relational nature of the affordance concept, Lanamäki et al. (2016) suggested four stances of affordance theory in IS research: (1) affordances arise from the relation between IT artifacts and social conventions (canonical affordances), (2) designers can embed affordances into IT artifacts with an imagined user in mind (designed affordances), (3) affordances are ever-present potentials for action, and their appropriation depends on users' goals and capabilities (potential affordances), and (4) affordances are enacted by users through actions within social practices (affordances as completed actions). Similarly, Mesgari et al. (2023) argued that the theoretical understanding of the affordance concept can be attributed to different research agendas. They distinguished between (1) the technical research stream focusing on the design of the interaction between user and IT artifact, (2) the organizational research stream emphasizing interactions between institutional routines and the IT artifact and their effects on an organizational level, and (3) the socio-behavioral stream applying the affordance concept to study contextual IT use behaviors and their effects on both the individual and group levels.

Throughout the work on my dissertation project, I moved away from the view that there must be one correct way of understanding and applying affordances in IS research. Instead, I concluded that different research agendas require different theoretical understandings of the concept, and the results of such diverse studies complement each other. The first research question of this dissertation focuses on the design of AR and VR systems to promote the achievement of user goals. Accordingly, these studies can be assigned to the technical research stream (Mesgari et al., 2023) and are based on the theoretical understanding of designed affordances (Lanamäki et al., 2016). The second research question considers context-specific behavior in the realization of affordances and its influence on subjective goal achievement at the individual and group levels. They can thus be assigned to the socio-behavioral research stream (Mesgari et al., 2023) and are based on the understanding of potential affordances (Lanamäki et al., 2016). Figure 1 shows how the two research perspectives complement each other to answer the research questions of this thesis. The following chapter provides a more detailed background on the relation between the affordance concept and effective use from a technical and socio-behavioral perspective.

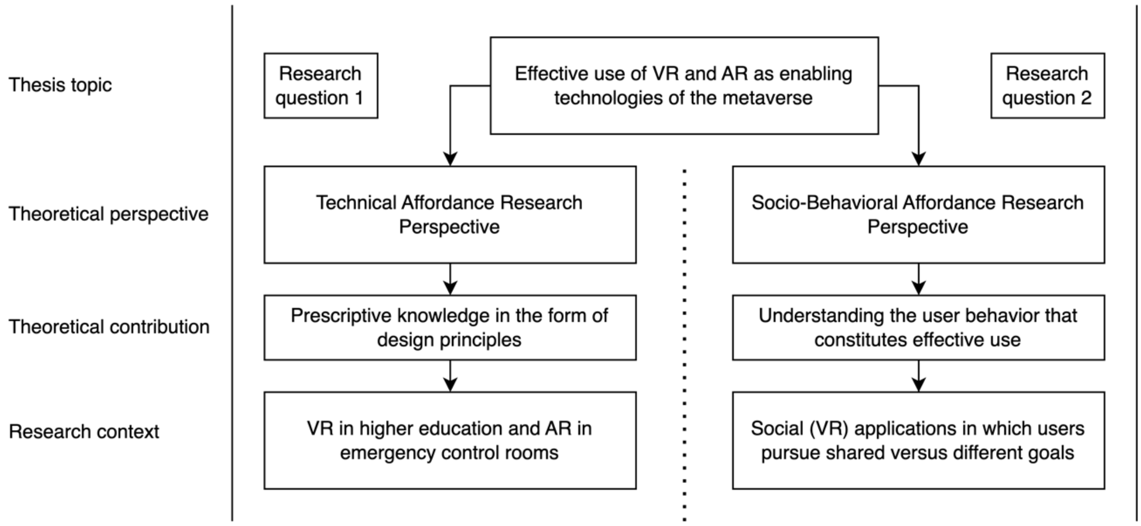

Figure 1. *Complementing affordance research perspectives*

2.3 The relationship between the affordance concept and effective use

Effective use is defined as *"that type of use that helps users attain desired goals"* (Burton-Jones & Volkoff, 2017, p. 469). The outcome of effective use is the achievement of user goals consisting of the dimensions of (1) effectiveness, referring to the degree of goal achievement and (2) efficiency, referring to the degree of goal achievement for a given input, such as effort or time (Burton-Jones & Grange, 2013). The dimensions of goal achievement can be measured using self-report items (Trieu et al., 2022) or objective measures of performance (Burton-Jones & Straub, 2006). The affordance concept is well suited to studying effective use because affordances are *"possibilities for goal-oriented actions"* (Markus & Silver, 2008, p. 622) and thus goal orientation is an inherent part of the definition. Since affordances are merely action potentials, users need to realize these potentials in order to achieve their goals. Strong et al. (2014, p. 54) distinguished between affordances as action potentials and affordance actualization as *"the actions taken by individuals to realize those potentials"*. For effective use, it is thus critical that users engage in affordance actualizations that contribute to goal achievement.

A technical perspective on effective use allows to understand how the design of IT artifacts facilitates the perception of affordances whose actualization contributes to goal achievement (Mesgari et al., 2023). Prior to affordance actualization, users construct beliefs about whether the actualization will afford or constrain goal achievement (Boukef & Charki, 2019; Jung & Lyytinen, 2014; Leonardi, 2011). This sense-making process might yield different results depending on users' goals (Chan et al., 2019; James et al., 2019) and mental models (Mettler & Wulf, 2019). Furthermore, the perception of affordances has a positive influence on the formation of beliefs about system quality (Grgecic et al., 2015), usability (Benbunan-Fich, 2019), and utility (James et al., 2019).

In the field of human-computer interaction, Norman (1988) applied the affordance concept to the design of everyday objects, suggesting that designers could influence the perception of intended affordances. For example, thin vertical door handles suggest that a door needs to be pulled, while flat horizontal plates communicate that a door needs to be pushed. If an object does not provide sufficient perceptual information about affordances, they might not be perceived by the user, or the user might try to use the object in an unintended way, for instance, when users try to push a door that needs to be pulled (Gaver, 1991). Building on these ideas, Maier and Fadel (2009) proposed the affordance-based design approach in the field of engineering, suggesting that designers should specify an IT artifact's properties with the goal of creating affordances and avoiding constraints for a specific user group. In IS research, it has also been proposed that a system needs to effectively communicate meaning so that users are able to perceive its affordances (Grgecic et al., 2015). Furthermore, IS researchers have applied the affordance-based design approach to propose design principles that enable the perception of specific affordances (Pan et al., 2021; Seidel et al., 2018).

A socio-behavioral perspective on effective use allows to understand how the affordance actualization behavior of users contributes to goal achievement in specific contexts (Mesgari et al., 2023). The actualization of each affordance is associated with an immediate concrete outcome that might lead to the emergence of new affordances (Strong et al., 2014). Such outcomes might be a necessary condition for the actualization of higher-level affordances, also called strong dependency; alternatively, they enable the actualization of further affordances, without being a necessary condition, also referred to as weak dependency (Burton-Jones & Volkoff, 2017; Krancher et al., 2018; Leidner et al., 2018;

Seidel et al., 2013; Strong et al., 2014). Furthermore, IS researchers have found that organizational goals can be achieved through the aggregated outcomes of individual actualization actions (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Strong et al., 2014). Contextual factors, such as user motivation, user competence and knowledge, organizational culture, leadership, training, usability, availability of technical infrastructure, and internet access, can enable or hinder the actualization of affordances (Argyris & Ransbotham, 2016; Du et al., 2019; Hatakka et al., 2020; Jiang & Cameron, 2020; Karlsen et al., 2019). Users evaluate the actualization outcomes in light of their goals and might improve their IT knowledge, routines, or the materiality of the IT artifact to achieve more desirable actualization outcomes in the future (Du et al., 2019; Leonardi, 2011; McKenna, 2020; Strong et al., 2014; Tim et al., 2018). Taken together, effective use can be understood as successfully actualizing a set of affordances, resulting in desired outcomes that contribute to an overarching goal (Burton-Jones & Volkoff, 2017).

In the IS field, researchers applied the affordance lens to examine effective use in an educational context and found that the actualization of affordances, such as collaboration and interactivity, has a positive influence on the perception of learning goal achievement (Beach & O'Brien, 2015; Jayarathna et al., 2020).However, in the context of an analytics-driven transformation, researchers have emphasized that each transformation phase requires the actualization of different affordances to achieve digital transformation goals (Tim et al., 2020; Zeng et al., 2020). To map the set of interrelated affordances that need to be actualized for goal achievement, Burton-Jones and Volkoff (2017) proposed the affordance network approach. The building blocks for an affordance network are so-called affordance-outcome units, as depicted in Figure 2.

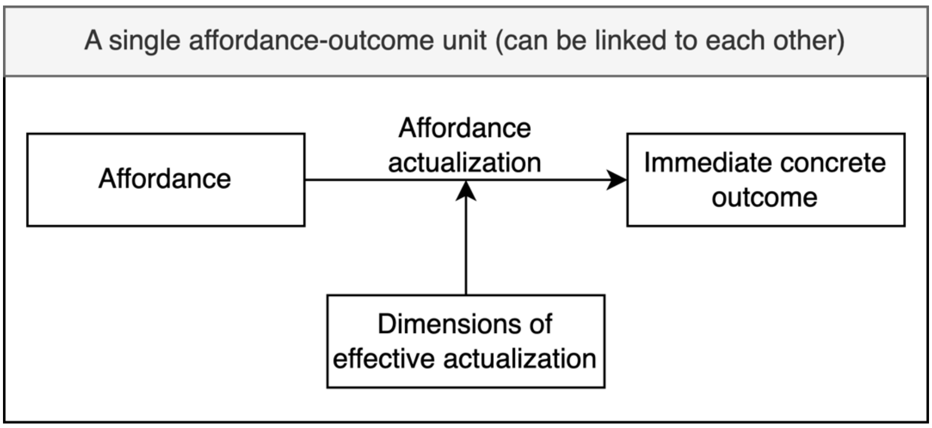

Figure 2. *Affordance-outcome unit as building block for an affordance network (adapted from Burton-Jones & Volkoff, 2017)*

Each unit consists of an affordance and an actualization action that leads to an immediate concrete outcome. The affordance-outcome units are interrelated, meaning that the outcome of the first unit (e.g., relevant data entered) enables the actualization of further affordances (e.g., data accessing affordance), and so on. Dimensions of effective actualization refer to differences in actualization actions that might influence the achievement of outcomes (e.g., consistent vs. inconsistent actualization of a data inputting affordance). In a study on fitness wearables, Abouzahra and Ghasemagaei (2022) applied the affordance network approach and found that some users did not achieve their ultimate goal of activity improvement because they only actualized affordances associated with the achievement of activity monitoring and planning goals. They also proposed that other users of fitness wearables have an influence on affordance actualization. For instance, friends encouraged users to actualize a social sharing affordance which was identified as important for achieving the ultimate goal of activity improvement.

3 Research design

3.1 Research strategy

This cumulative dissertation consists of two parts that aim to explore the effective use of VR and AR through an affordance lens. The first research question aims to propose design principles for the effective use of VR and AR systems while the second research question explores the effective use of social (VR) applications in contexts where users pursue shared versus different goals on the same platform. Table 2 depicts how each publication contributes to answering the research questions.

This dissertation includes three papers addressing the first research question. Paper 1 and 2 focus on the design of effective VR learning applications for higher education. Paper 3 proposes design principles enabling the effective use of AR for emergency management. The remaining four papers address the second research question. In paper 4, methodological guidelines for applying the affordance concept to study phenomena, such as effective use were developed. These guidelines were adhered to in the following papers. Paper 5 shows how a group of students actualized an interrelated set of VR affordances to achieve their shared collaborative learning goals. Paper 6 examines the role of VR affordances and constraints in the occurrence of negative group effects during a student group task. Paper 7 shows how social movements for climate justice and organizations pursuing different environmental policy goals mutually influence each other in their actualization of social media affordances, and thus effective use.

Table 2. *Papers associated with the research questions*

Paper	Title	RQ1	RQ2
1	A Systematic Review of Immersive Virtual Reality Applications for Higher Education: Design Elements, Lessons Learned, and Research Agenda	X	
2	More than Experience? - On the Unique Opportunities of Virtual Reality to Afford a Holistic Experiential Learning Cycle	X	
3	Social Media Data in an Augmented Reality System for Situation Awareness Support in Emergency Control Rooms	X	
4	A Systematic Review of Empirical Affordance Studies: Recommendations for Affordance Research in Information Systems		X
5	Virtual Reality in Digital Education: An Affordance Network Perspective on Effective Use Behavior		X
6	Effects of Virtual Reality Affordances and Constraints on Negative Group Effects during Brainstorming Sessions		X
7	Paradoxical Tensions Between Social Media Affordances and Constraints for Collective Action – Analysing the Interplay of Organisations Pursuing Different Environmental Policy Goals		X

3.2 Applied research methods

Within this paper-based dissertation, mostly qualitative research methods were applied, which are well suited to answering "how" and "why" research questions, building theory in new areas, and providing rich insights into the subjective views of respondents (Flick et al., 2004). Furthermore, qualitative research methods are most often applied in affordance research in the IS field, since affordances are often perceived differently by various users (Fromm et al., 2020). Table 3 provides an overview of the conducted research approaches, including their data collection and analysis methods. A systematic literature review was conducted in paper 1 and 4, following established guidelines in IS research (vom Brocke et al., 2015; Webster & Watson, 2002). Systematic literature reviews are well suited to synthesize research in a field, uncover research gaps, identify methodological approaches that are common in an area, and develop an agenda for future research (vom Brocke et al., 2015). In papers 3, 5, 6, and 7, semi-structured interviews were used as the main data collection method which allows researchers to alter or restructure the questions during the interview, ensuring that all relevant topics are covered (Myers & Newman, 2007). Observations were used as an additional data collection method in paper 5 to capture unconscious or automatized behaviors of the respondents (Döring & Bortz, 2016). In paper 2, design thinking workshops (Brown, 2008) were conducted to develop and evaluate prototypes as part of design-oriented research (Devitt & Robbins, 2012; Dolak et al., 2013). In papers 2 and 3, focus group discussions were used as an established method for artifact evaluation and refinement in design research (Tremblay et al., 2010). A qualitative content analysis was conducted to analyze data collected through interviews, observations, focus groups, and workshops (Mayring, 2014).

Table 3. *Overview of applied research methods*

Paper	Research approach	Data collection method(s)	Data analysis method(s)
1	Qualitative (descriptive)	Systematic literature review	Literature research
2	Qualitative (descriptive)	Design thinking workshops, focus group discussions with prototypes	Content analysis
3	Qualitative (descriptive)	Interviews, focus group discussions with prototype	Content analysis
4	Qualitative (descriptive)	Systematic literature review	Literature research
5	Qualitative (explanatory)	Interviews, observations	Content analysis
6	Qualitative (explanatory)	Interviews	Content analysis
7	Qualitative (explanatory)	Interviews	Content analysis

4 Research results

This research examines (1) design principles enabling the effective use of VR in higher education and AR in emergency control rooms, as well as (2) the behavior that constitutes effective use of social (VR) applications where users pursue shared versus different goals on the same platform. The results chapter is structured as follows: First, the results for the first research question are presented. Papers 1 and 2 focus on the design of effective VR learning applications in higher education. Paper 3 proposes design principles for the effective use of AR in emergency management. Second, the results for the second research question are reported. Paper 4 introduces methodological recommendations for affordance research that were followed in the subsequent research papers. Papers 5 and 6 focus on the influence of other users who were pursuing the same goals on the effective use of social VR applications in a collaborative learning context. Paper 7 provides insights into the influence of users with different environmental policy goals on the effective use of social media in the context of collective action.

4.1 Technical affordance perspective: Designing for the effective use of VR in higher education and AR in emergency control rooms

The goal of paper 1 was to provide a comprehensive overview of the state of the art on the design of VR applications for higher education. Specifically, the authors aimed to identify design patterns for effective use based on previous research, that is, VR design elements that can be implemented to achieve specific learning goals. The authors used a search term that included keywords related to VR, learning, and higher education to search for relevant articles in four electronic databases (i.e., IEEE Xplore Digital Library, ProQuest, Scopus, and Web of Science). The initial search yielded 3,219 articles, out of which the authors analyzed 38 relevant articles after a two-step semi-automatic and manual exclusion process. The included articles described the design, use, and in some cases, the evaluation of VR applications for higher education. The results showed that, in previous design-oriented research, VR design elements were not adapted depending on the intended learning goal. The intended learning goals in descending order were teaching procedural-practical knowledge (33%), declarative knowledge (26%), analytical and problem-solving skills (12%), and communication and collaboration skills (10%). Overall, the authors identified fourteen VR design elements for higher education of which basic interaction (24%) and realistic surroundings (17%) were most frequently used. As shown in Figure 3, a systematic mapping of VR design elements and learning goals revealed that basic interaction and realistic surroundings were implemented regardless of the learning goal. Furthermore, VR applications aiming to teach declarative knowledge mostly only included these two design elements, while a larger number of design elements were used to achieve more complex learning goals, such as gaining procedural-practical knowledge. Other than that, the systematic mapping did not reveal any clear patterns regarding which VR design elements could be implemented to effectively use VR for the achievement of specific learning goals. A reason could be that the large majority of studies did not ground the development of VR applications on learning theories (68%) and almost half of the articles did not mention any evaluation of learning outcomes to assess the effectiveness of the design (46%). Altogether, the systematic literature review highlighted the development of design principles that foster the achievement of specific learning goals in higher education as a research gap, which was addressed in paper 2.

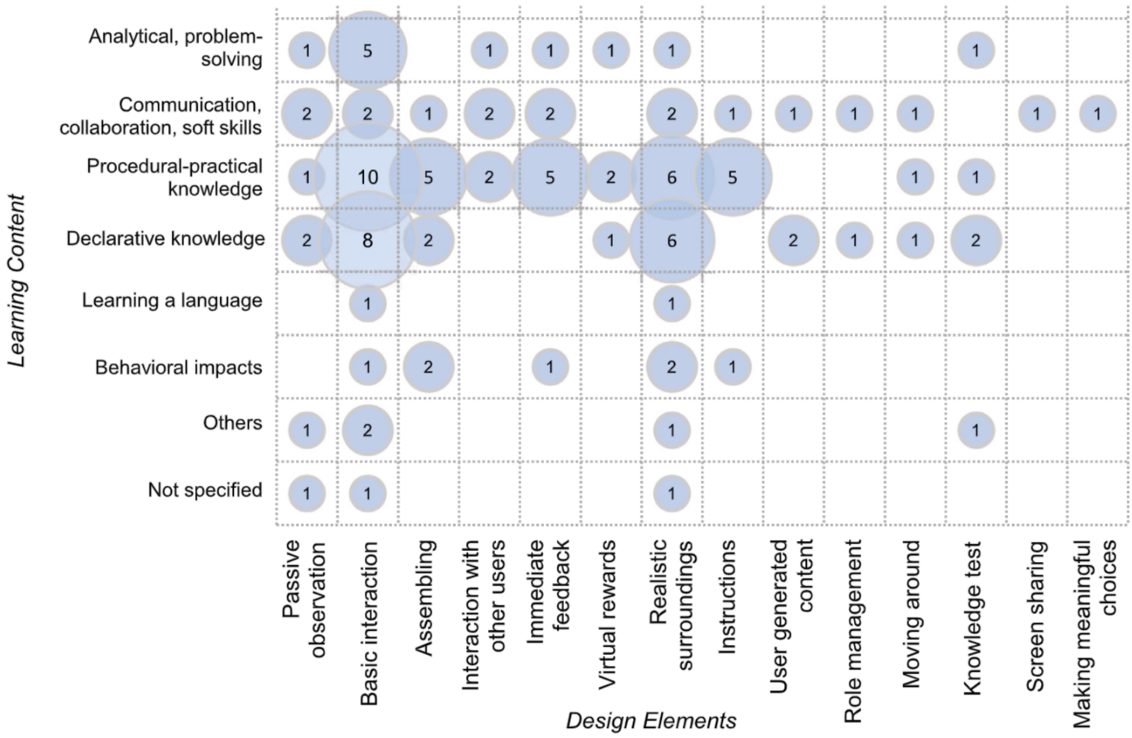

Figure 3. *Systematic mapping of VR design elements and learning goals (paper 1)*

Paper 2 builds on paper 1 by developing design principles for educational VR applications targeting a specific learning objective. In contrast to the design-oriented studies reviewed in paper 1, the authors included students as the intended user group throughout the entire design process to find out what learning goal students want to achieve with VR and what affordances they desire for this purpose. Following an affordance-based design approach, the authors conducted three design thinking workshops in which 18 lecturers and eight students participated. In each workshop, the participants conducted interviews with students on campus to understand their learning goals and desired VR affordances. The interviews showed that students would like VR to improve procedural-practical knowledge and provide experiential learning affordances. Thus, the workshop participants developed low-fidelity VR prototypes that could afford an experiential learning process. The developed prototypes could best be described as job simulators (i.e., VR Business Pitch, VR

Emergency Team, and VR Classroom Simulator). According to experiential learning theory (Kolb, 1984), a holistic experiential learning process consists of four learning modes (i.e., concrete experience, reflective observation, abstract conceptualization, and active experimentation). In three focus group discussions with 17 students, the three VR prototypes were evaluated and refined to afford all four experiential learning modes. The developed prototypes show which of the design elements identified in paper 1 can be implemented to provide experiential learning affordances fostering the effective use of VR for improving procedural-practical knowledge. Of the design elements identified in paper 1, realistic environments and scenarios, character movement, and interaction with objects and users were found to be particularly relevant to afford the experiential learning modes of concrete experience and active experimentation. In addition, interaction with intelligent agents was identified as an important design element, indicating that users expect to be able to use VR more effectively when designers exploit the synergies between the affordances enabled by VR and artificial intelligence. The students also suggested VR design elements to afford the experiential learning modes of reflective observation and active experimentation (e.g., passive observation, instructions, and feedback). However, the students emphasized that these affordances could probably be better provided by existing means of teaching (e.g., discussions in the classroom, presenting slides, and reading textbooks). They did not perceive a particular strength of VR in providing these affordances, suggesting that VR may be used most effectively as a complement to existing teaching approaches. To synthesize the findings, the authors derived the following six design principles that should be considered to enable the effective use of VR-based experiential learning applications for improving procedural-practical knowledge:

1. Principle of technical and pedagogical considerations: Identify both the unique technical opportunities of VR and pedagogical requirements.

2. Principle of knowledge contextualization: Enable students to apply theoretical knowledge in realistic job scenarios.

3. Principle of realism and interactivity: Provide a realistic and interactive virtual environment to afford concrete experience and active experimentation.

4. Principle of integration: Cycle between concrete experience and active experimentation activities in VR and reflective observation and abstract conceptualization activities in class.

5. Principle of psychological comfort: Provide students with the opportunity to practice skills in private spaces before allowing other students to join their learning space.

6. Principle of gamification: Embrace the gaming character of VR to increase learning motivation.

Paper 3 aimed to propose a design for an AR system that fosters the achievement of situation awareness goals in emergency control rooms. In this context, it was also explored how the integration of social media data can contribute to the achievement of situation awareness goals. Similar to paper 2, the authors adopted a user-centered design approach and involved emergency operators throughout the entire design process. The authors conducted a goal-directed task analysis to identify emergency operator goals, decisions that need to be made to accomplish these goals, and situation awareness requirements that are mandatory for decision-making. To accomplish this analysis, the authors conducted expert interviews with nine emergency operators working in fire departments in Germany. The goal-directed task analysis revealed two major goals of emergency operators: 1) dispatching emergency forces and 2) supporting emergency operations. For both goals, information about the location of the emergency emerged as the most important situation awareness requirement because it enabled operators to at least send emergency forces who could then gather further information. Afterwards, the authors assessed which situation requirements could be fulfilled by integrating social media data into emergency control rooms. Therefore, the authors collected Twitter data during storms Eberhard and Dragi, which hit Germany in 2019. The authors conducted a second round of expert interviews with five emergency operators to assess the usefulness of the tweets gathered. The results showed that emergency operators perceived traffic information from transport business organizations as particularly useful and trustworthy. Eyewitness reports were also perceived as useful, but trustworthiness was questioned. Other types of tweets were rated as not useful because they did not provide relevant information (e.g., emotional tweets) or redundant information (e.g., informational tweets from media organizations). Finally, the authors proposed a conceptual AR design, illustrated in Figure 4, by following design principles for situation awareness (Endsley et al., 2003) and evaluated the design in a focus group discussion with two AR experts and two situation awareness experts. As with paper 2, it was found that the design for effective use of AR in emergency control rooms should consider the extent to which the technology can provide unique affordances compared with existing information systems. The evaluation workshops revealed that the strength of AR was perceived as providing unique affordances for organizing information (e.g., more freedom in arranging information in an operator's field of view), affordances for visualizing information (e.g., better comprehension through three-dimensional representation of building models), and affordances for enriching information (e.g., deeper insights through overlaying building models with photos and videos from social media).

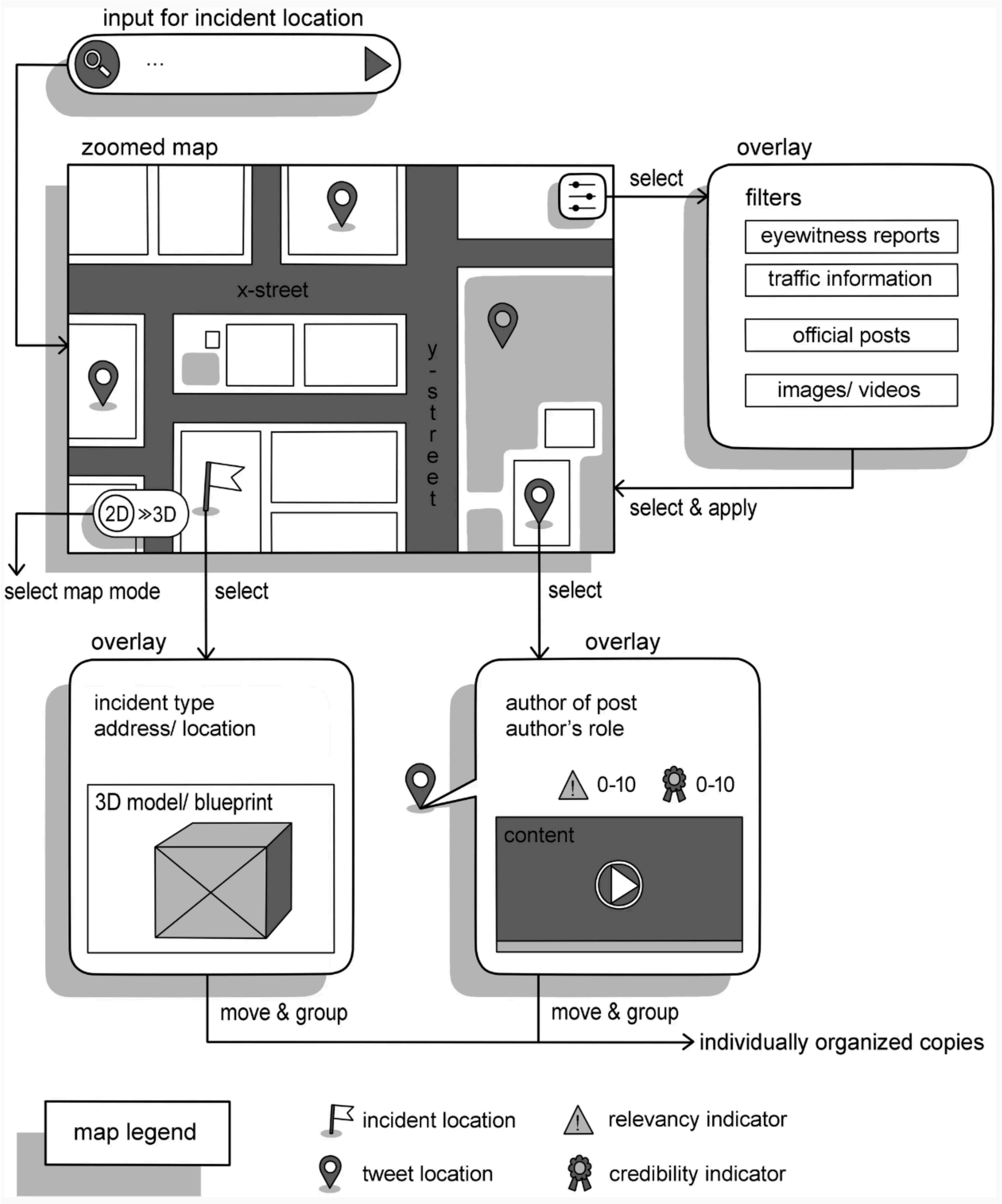

Figure 4. *Conceptual AR design for situation awareness support (paper 3)*

4.2 Socio-behavioral affordance perspective: Effective use of social (VR) applications where users pursue shared versus different goals

The goal of paper 4 was to provide methodological guidance on how to apply the affordance concept to investigate IS phenomena, such as effective use. The authors searched for the term "affordance" in the electronic databases Scopus and AISeL to include the most relevant IS journals and conference proceedings. The search yielded 453 articles, out of which 152 articles remained after applying the inclusion and exclusion criteria. As part of the research-in-progress paper, the authors analyzed 29 journal articles using a concept-centric approach (Webster & Watson, 2002). From the relevant articles, the authors extracted data regarding the concepts of technology type, application area, technology affordances, research design, research methods, and methodological best practices. The results showed that the affordance concept has been applied more frequently in empirical IS studies with each passing year since 2011. Furthermore, 86% of the studies applied a qualitative research design using methods such as case studies, field studies, interviews, document analysis, observations, focus groups, artifact analysis, and usage data analysis. Most studies investigated the affordances of social media (28%). In these studies, 67 social media affordances were identified, with a mention of only seven affordances in more than one article. This highlights the problem that almost all studies add new affordances to an already exhausting list, since a shared labeling practice does not exist, and affordances are often defined on different levels of abstraction. By synthesizing the methodological best practices applied in the relevant articles, the authors derived the following eight recommendations for affordance research in the IS field:

1. Aim for a mid-range theory when using the affordance concept to explain IS phenomena.
2. Apply critical realism as a research paradigm.
3. Separate affordances from technology features, use, and usage outcomes.
4. Consider the relational nature of the affordance concept.
5. Show the interrelations and interactions between multiple affordances.
6. Identify contextual factors enabling or inhibiting affordance actualization.
7. Analyze the paradoxical tension between technology affordances and constraints.
8. Apply affordances identified in previous literature.

These methodological recommendations advance the principles of affordance research proposed by Volkoff and Strong (2017) by enriching them with specific implementation suggestions based on previous research. In the further course of my dissertation, the elaborated methodological recommendations served as guidelines in conducting the empirical studies on effective use from a socio-behavioral perspective. For example, paper 5 showed the interrelations between multiple affordance actualizations (recommendation 5). Papers 5 and 7 consider the influence of other actors on affordance actualization (recommendation 6). Furthermore, papers 6 and 7 analyze the influence of constraints on affordance actualization (recommendation 7). Other recommendations, such as considering the relational nature of the affordance concept and separating affordances from technology features, uses, and usage outcomes, were of a more general nature and were taken into account across all papers contributing to the second research question.

The goal of paper 5 was to understand the affordance actualization behavior that constitutes effective use of social VR in a collaborative learning context (i.e., a context in which users pursue shared goals on the same platform). To gain insights, I delivered six sessions of a bachelor's course titled "Communication & Collaboration Systems" using the social VR application Spatial. The authors conducted two rounds of interviews with the nine student participants (overall 18 interviews) and six observations of the course sessions. The interviews revealed affordance bundles whose actualization resulted in outcomes that in turn facilitated the actualization of other affordance bundles, as can be seen in Figure 5. For example, the actualization of interactivity, self-presentation, navigability, and embodied cognition resulted in the outcome of an increased feeling of immersion and presence, which facilitated the actualization of affordances, resulting in a decreased interpersonal distance. The results showed that affordance actualization at the level of social interaction mainly contributed to the goal of regular and active participation in the lecture. Effective use, in terms of achieving the goals of knowledge gain, skill development, and academic success, however, required the actualization of higher-level affordances, such as multimodality, content aggregation, collaboration, and persistence. The dimensions of effective actualization (i.e., degree of skill, variety, task orientation, and activity in affordance actualization) also had an influence on the level of effective use that could be achieved. Student peers supported each other in the effective actualization of affordances (e.g., by suggesting different ways to actualize an affordance, resulting in a better outcome, and thus more effective use). The results further showed that students who merely actualized lower-level affordances instead of pursuing actions related to the ultimate goal of knowledge gain distracted other students from affordance actualization, and thus constrained their effective use. In summary, this paper highlights the interrelations of affordance actualizations required to achieve shared learning goals, how the affordance actualizations of student peers might create constraints for goal achievement, and the encouraging social influence of student peers (recommendations 5, 6, and 7 from paper 4).

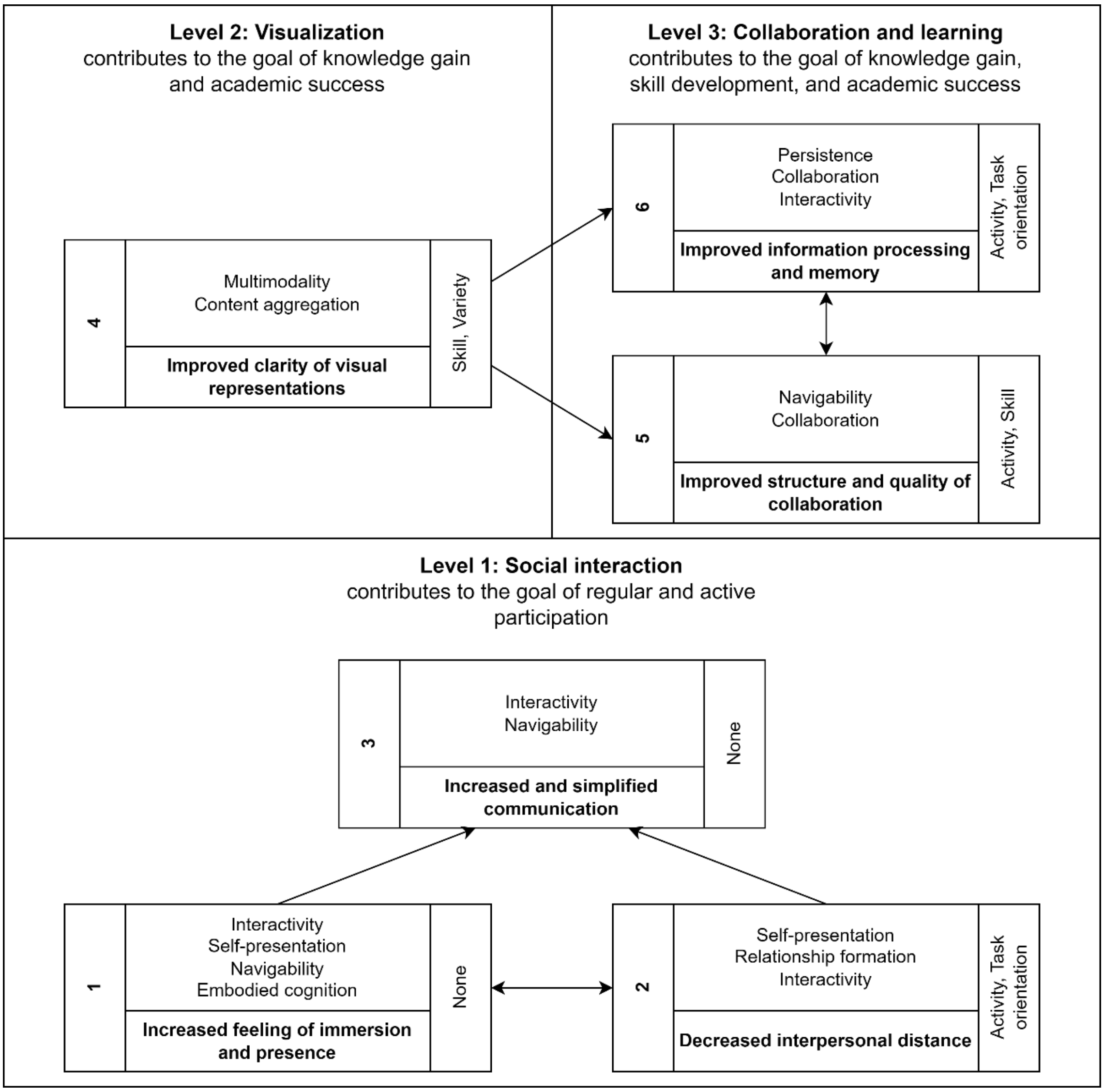

Figure 5. *Affordance network (paper 5)*

Paper 6 also examined the behavior that constitutes the effective use of social VR for collaborative learning (i.e., a context in which users pursue shared goals). Compared to paper 5, the study considers the influence of technical constraints on effective use and aims to explain the occurrence of negative group effects as a hindrance to goal achievement. To investigate this topic, six groups of three students each ($N = 18$) were given 12 minutes of time to work on a group task. To do so, the participants used an Oculus Go and the social VR application vTime XR. Afterwards, the authors interviewed each participant to explore the reasons for the occurrence of negative group effects. Production blocking was the most common negative group effect in the VR environment (44%), followed by evaluation apprehension (17%), social comparison (11%), and cognitive inertia (11%). Of these, only production blocking and evaluation apprehension could be associated with VR affordances and constraints. Figure 6 visualizes an affordance and constraint network explaining the occurrence of these negative group effects. The results showed that the participants expected certain affordances, such as being able to express themselves through facial expressions and gestures. However, the limitations of the VR hardware and software (e.g., pre-programmed facial expressions / gestures, pointer controller, fixed seating arrangement, and delays) constrained the participants in their communicative actions. The attempted actualization of constraints resulted in immediate concrete outcomes (e.g., increased uncertainty about each other's reactions), which in turn manifested in negative group effects (e.g., evaluation apprehension). Overall, the paper emphasizes how the interplay of affordances and technical constraints might hinder groups at achieving their shared usage goals, and thus effective use (recommendation 7 from paper 4).

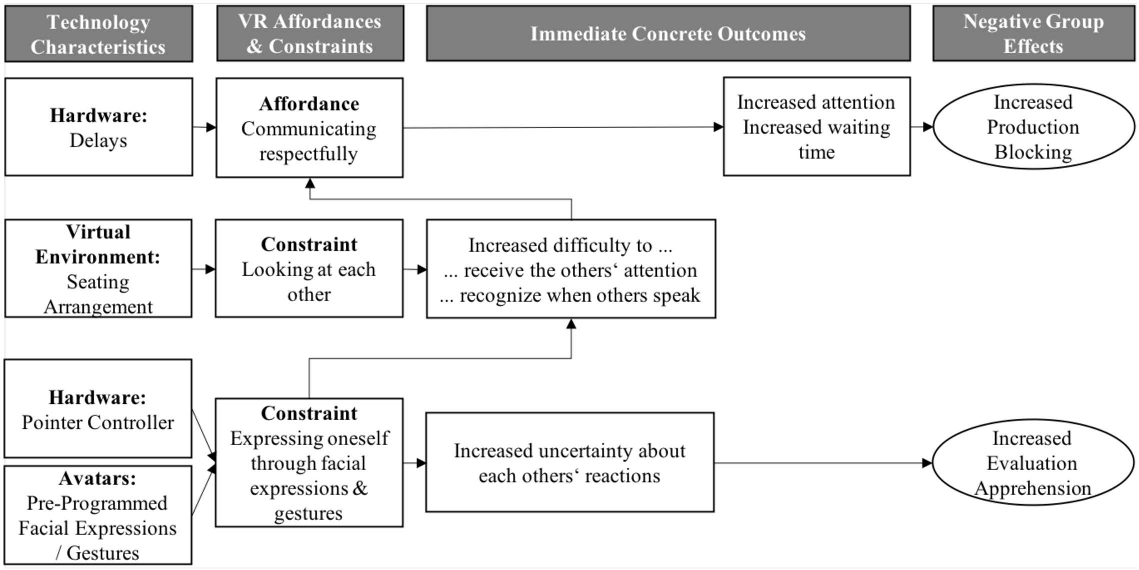

Figure 6. *Affordance and constraint network (paper 6)*

The goal of paper 7 was to understand the behavior that constitutes effective use in a contrasting context where users pursue different goals on the same social platform. To achieve this, the authors conducted interviews with thirty social media managers of social movements for climate justice (i.e., Fridays for Future, Vegans for Future, Health for Future, Students for Future, and Scientists for Future). Furthermore, the authors interviewed six members of organizations pursuing different environmental policy goals (i.e., Alternative for Germany, German Combustion Engine Association, and Schleswig-Holstein Farmers' Association). The interviews revealed three tensions between social media affordances and constraints arising from the interaction of actors pursuing different goals: (1) tension between the affordance of informational education and the constraint of false information, ideology, and propaganda; (2) tension between the affordance of emotional storytelling and the constraint of (shadow) bans and content deletion; and (3) tension between the affordance of interactive networking and the constraint of hate speech and coordinated shitstorms. The tensions highlight that affordance actualization results in positive outcomes contributing to goal achievement, but at the same time, affordance actualization can result in constraints diminishing these positive outcomes. For example, actualizing the emotional storytelling affordance with a focus on negative emotions temporarily increases the reach (positive outcome), but when taken to the extreme, it can lead to the constraint of (shadow) bans and content deletion reducing the reach (diminished outcome). As in papers 5 and 6, constraints have been shown to be an obstacle to goal achievement. Similar to paper 5, it has been revealed that not only constraints that arise due to technical limitations are relevant. Constraints can either be self-imposed by the manner of one's own affordance actualization (e.g., actualizing the emotional storytelling affordance with a focus on negative emotions) or emergent through the affordance actualizations of actors pursuing different goals (e.g., other actors actualize the interactive networking affordance by coordinating shitstorms, which is perceived as a constraint by the affected organization). Overall, the study reveals the influence of other users and constraints on the effective use of social media, where users pursue different goals (recommendations 6 and 7 from paper 4).

5 Discussion

5.1 Technical affordance perspective: Designing for the effective use of VR in higher education and AR in emergency control rooms

There are already numerous design-oriented papers presenting VR applications for higher education (e.g., Al-Gindy et al., 2020; Ding et al., 2020; Hernández-Chávez et al., 2021) or AR systems for emergency management (e.g., Brandao & Pinho, 2017; Brunetti et al., 2015; Luchetti et al., 2017; Nunes et al., 2019). These primarily highlight the unique technological capabilities of VR and AR and then describe a system architecture in detail without involving users in the design process. A systematic literature review on VR in higher education confirmed that many design-oriented papers portray the development process without considering the learning goals students want to achieve (paper 1). This could lead to an unwillingness to actualize affordances as users construct beliefs about whether an application will afford or constrain goal achievement (Boukef & Charki, 2019; Jung & Lyytinen, 2014; Leonardi, 2011). Therefore, in papers 2 and 3, users were involved throughout the entire design process, with the aim of creating affordances for the respective user group and avoiding constraints, as suggested by the affordance-based design approach (Maier & Fadel, 2009; Pan et al., 2021; Seidel et al., 2018).

Both papers 2 and 3 demonstrate the value of carefully analyzing user goals when designing VR and AR systems with the aim to foster effective use. By involving users in the design process, paper 2 indicated that students across different subjects desire a VR application to support them in improving procedural-practical knowledge by providing experiential learning affordances. This shows a discrepancy between the affordances desired by students and those provided by VR applications already on the market, which tend to be designed to impart declarative knowledge (Radianti et al., 2021). In paper 3, emergency operators were involved in the design process to propose an AR system that integrates social media data in a way that affords decision-making in control rooms. In this context, critical decisions must be made under time pressure, and thus, it is important that the visualization of additional information does not increase cognitive load (Mirbabaie & Fromm, 2019). Through an analysis of emergency operator goals in paper 3, traffic information and eyewitness accounts were identified as the only social media information that could add value in achieving situational awareness goals. Thus, when designing AR systems to integrate additional information into emergency control rooms, the development of filtering algorithms adapted to operator goals is essential for effective use (Kaufhold et al., 2020; Stieglitz et al., 2018).

Furthermore, papers 2 and 3 show that it is important to consider how VR and AR in combination with existing systems are able to generate desired affordances (Burton-Jones & Volkoff, 2017; Lehrer et al., 2018). To enable a holistic experiential learning process, affordances for concrete experience, reflective observation, abstract conceptualization, and active experimentation are needed (Kolb, 1984). However, to provide affordances for reflective observation and abstract conceptualization, paper 2 did not reveal any VR design elements that could add value over traditional teaching methods (e.g., discussions in class, presenting slides). The reasons for this are technical constraints, such as the insufficient representation of facial expressions and gestures in avatars and the low resolution of slides uploaded in VR environments. This highlights that VR is best designed, at least currently, as a supplement to traditional teaching means. Similarly, a study on Second Life showed that students used the virtual environment for concrete experience and active experimentation, while reflective observation and abstract conceptualization took place outside the virtual environment (Jarmon et al., 2009). In the context of emergency management, previous AR systems have been limited to displaying messages and icons in the responders' field of view, such as text boxes with patient health information or beacons for the locations of other responders (e.g., Brandao & Pinho, 2017; Brunetti et al., 2015; Luchetti et al., 2017; Nunes et al., 2019). In field operations, this use of AR may add value, but emergency control rooms already have six to seven screens displaying information from multiple data sources. This means that social media information could easily be displayed on an additional screen. The question then arises: How could AR provide an added value in combination with existing information systems?

Regarding this, papers 2 and 3 highlight that to design for effective use, it is important to make the unique affordances of VR and AR perceptible (Steffen et al., 2019). For example, paper 2 shows that VR offers unique opportunities to provide experiential learning affordances for concrete experience and active experimentation through immersive and interactive design elements (e.g., realistic surroundings and scenarios, interaction with objects, users, and intelligent agents). In the context of emergency management, paper 3 reveals that AR can provide unique affordances for organizing information, visualizing information, and enriching information, although the technical implementation currently still poses a considerable challenge. For example, a tweet should not only be displayed as a message overlay on a map, but the included image content could also be mapped onto a 3D building object to give a better visual impression of the extent of a fire and the accessibility of escape routes. This would require the creation of high-quality 3D building objects, and that using image recognition software, the section of an affected building can be correctly identified and mapped.

In summary, designing for the effective use of VR in higher education and AR in emergency management involves carefully analyzing user goals, considering how VR and AR can create affordances in combination with existing systems, and making the unique affordances of VR and AR perceptible.

5.2 Socio-behavioral affordance perspective: Effective use of social (VR) applications in which users pursue shared versus different goals

The affordance concept has been proposed as promising for analyzing what constitutes effective use in specific contexts, which has often been treated as a black box in previous research (Burton-Jones & Volkoff, 2017). To enable the meaningful application of the concept, Volkoff and Strong (2017) proposed principles for affordance research in the IS field. However, it has been criticized that the affordance concept is still only seldom used to explain relevant IS phenomena, and studies often do not go beyond identifying new affordances of emerging technologies (Berente & Recker, 2021). By deriving methodological recommendations based on a review of empirical affordance studies, paper 4 concretizes the principles for affordance research developed by Volkoff and Strong (2017). Paper 4 revealed that a meaningful application of the affordance concept (for example, to explain effective use) should involve an analysis of (1) interdependencies between affordances, (2) contextual factors enabling and hindering affordance actualization, and (3) tensions between affordances and constraints. These factors were considered in empirical studies on the effective use of social (VR) applications where users pursued shared versus different goals on the same platform (papers 5, 6, and 7). While papers 5 and 6 focus on the effective use of social VR applications for collaborative learning, paper 7 analyzes the effective use of social media for collective action as a contrasting context where users pursued different goals on the same platform.

Paper 5 demonstrated an application of the affordance network approach (Burton-Jones & Volkoff, 2017) to analyze what constitutes effective use of social VR applications in a collaborative learning context. Previously, the affordance network approach was applied to study the effective use of electronic medical record systems (Burton-Jones & Volkoff, 2017) and fitness wearables (Abouzahra & Ghasemaghaei, 2022). In these studies, a linear sequence of affordance actualizations and their associated outcomes constituted effective use. For example, the actualization of a data inputting affordance resulted in the outcome of entered data which was a necessary condition for the actualization of a data accessing affordance, and so on (Burton-Jones & Volkoff, 2017). The results of paper 5 suggest that the effective use of social VR applications has different characteristics. Effective use was characterized by the simultaneous actualization of multiple affordance bundles (Leidner et al., 2018; Volkoff & Strong, 2013), which resulted in immediate outcomes contributing to goal achievement. For example, students did not only actualize affordances resulting in the outcome of improved communication (i.e., interactivity, navigability) but also affordances resulting in the outcome of an improved visualization of knowledge at the same time (i.e., multimodality, content aggregation). Furthermore, the interrelations between affordances were characterized by weak dependencies (Strong et al., 2014), meaning that the actualization of affordances related to improved communication was not a necessary condition to actualize the affordances related to an improved visualization of knowledge.

Paper 5 also showed that affordance actualizations contributed to different levels of goal achievement. In some course sessions, students mainly actualized affordances contributing to the goal of regular and active participation in the lecture (i.e., interactivity, self-presentation, navigability, embodied cognition, and relationship formation), but did not engage in the actualization of affordances contributing to their ultimate goal of knowledge gain (i.e., content aggregation, multimodality, collaboration, and persistence). This aligns with previous research distinguishing between basic and higher-level affordances (Du et al., 2019; Krancher et al., 2018; Leidner et al., 2018; Strong et al., 2014; Volkoff & Strong, 2013). Furthermore, the results align with a study on fitness wearables in which some users only actualized affordances contributing to the goals of activity monitoring and planning but were not able to achieve their ultimate goal of activity improvement (Abouzahra & Ghasemaghaei, 2022).

Papers 5, 6, and 7 highlight the importance of dealing with constraints for goal achievement, and thus effective use. Therefore, the papers extend previous research showing that technology can both afford and constrain goal achievement (Ciriello et al., 2019; Leonardi, 2011; A. Majchrzak et al., 2013). In this regard, paper 6 shows how the technical limitations of VR hardware and software resulted in the perception of constraints and negative effects during student group work. For example, the limited possibilities of the Oculus Go pointer controller and pre-programed facial expressions made it more difficult for the students to interpret the reactions of their peers, which led to the negative group effect of evaluation apprehension.

Papers 5 and 7 revealed that not only the technical limitations, but also the different ways in which users actualize affordances can lead to the emergence of constraints. Thus, the results confirm prior research indicating that affordance actualization can result in unintended consequences (Tim et al., 2018). In paper 5, for example, some students used 3D objects only for the actualization of lower-level affordances, such as relationship building, which did not directly contribute to the achievement of their ultimate goal of knowledge gain. The other students reported that as a result, they were distracted from actualizing higher-level affordances (e.g., when a smaller group of students suddenly started to decorate the virtual environment with 3D objects). The unintended consequence of distractions might be particularly relevant when it comes to the effective use of social VR applications because the technology is still new for many, and users are often curious to try everything that is possible in the virtual environment. The constant representation by an avatar also makes it difficult to pursue other activities unnoticed, whereas in a video conference, for example, it is possible to open a new browser tab and pursue other activities.

Paper 7 focused on the effective use of social media for collective action, which is a contrasting context in which actors with different goals used the same platform. Thus, the paper answers the call for research on the influence of external stakeholders on organizational affordance actualization processes (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Sæbø et al., 2020). Paper 7 confirms that the way in which affordances are actualized depends on user goals (Strong et al., 2014). For example, social movements for climate justice actualized an interactive networking affordance by mobilizing their communities to jointly set Twitter trends, guided by their goal of effecting change. In contrast, actors pursuing different environmental policy goals actualized the same affordance by deliberately generating heated discussions, guided by the goal of increasing their reach before elections.

These different ways of actualizing one and the same affordance can lead to the emergence of constraints. Regarding this, paper 7 revealed that constraints can be self-imposed through a provocative manner of affordance actualization. For example, such actualizations can result in shadow bans and content deletions, making it more difficult to achieve the goal of an increased reach. Alternatively, paper 7 showed that constraints can arise from affordance actualizations by actors pursuing different goals. If these actualize the interactive networking affordance, for example, in the form of coordinated shitstorms, the affected organization may perceive this as an obstacle to goal achievement. To deal with constraints, actors either extended their actualization activities to other platforms (e.g., Telegram) or switched to more constructive ways of actualizing affordances (e.g., by moderating discussions more strictly). This is in line with previous research suggesting that users evaluate actualization outcomes considering their goals and might recognize new ways of affordance actualization over time (Du et al., 2019; Leonardi, 2011; McKenna, 2020; Strong et al., 2014; Tim et al., 2018).

While paper 7 emphasizes the potential negative influence of other users with regard to goal achievement, paper 5 shows that other users can also have a supportive influence on affordance actualization, and thus effective use. For example, students shared the results of their affordance actualizations with others and answered the questions of their peers often faster than the lecturer. Similarly, previous research found that colleagues (e.g., technical staff) could support affordance actualization by resolving constraints (Wang & Nandhakumar, 2016), or friends could set an encouraging example by actualizing affordances themselves (Abouzahra & Ghasemaghaei, 2022).

Altogether, the findings revealed that the effective use of social VR applications in a collaborative learning context involves the actualization of not only basic but also higher-level affordances associated with the overarching shared goal of knowledge gain. The effective use of social (VR) applications involves successfully dealing with constraints arising from both technical limitations and the affordance actualizations of actors pursuing different goals on the same platform. Furthermore, fostering the supportive influence of other users pursuing shared goals can encourage the actualization of higher-level affordances that contribute to goal achievement.

6 Conclusion

6.1 Theoretical implications

The first part of this thesis extends the technical affordance research stream in the IS field (Mesgari et al., 2023) by contributing prescriptive knowledge in the form of design principles for the effective use of VR in higher education and AR in emergency control rooms. The design-oriented studies in this part demonstrate the value of an affordance-based design approach that involves users in the design process (Maier & Fadel, 2009; Pan et al., 2021; Seidel et al., 2018). Designing for effective use requires an alignment between the goals users want to achieve and affordances that are made perceptible through design elements. It is important to consider how the design of VR and AR applications creates novel affordances that are not already perceived in existing information systems. In the context of VR in higher education, it was shown that a focus on creating affordances for concrete experience and active experimentation through immersive and interactive design elements can add value to the achievement of student goals, while other experiential learning modes can be better supported by existing learning media. With regard to AR in emergency control rooms, it became apparent that AR only adds value to existing information systems if the potential of 3D information visualization is fully exploited. This means that AR systems should not merely display textual information in an emergency operator's field of vision but should support the achievement of situation awareness goals, for example, by mapping visual social media content to a 3D map of the current situation.

The second part of this thesis advances the socio-behavioral affordance research stream in the IS field (Mesgari et al., 2023). First, the research in this part extends methodological recommendations guiding the meaningful application of the affordance concept to explain relevant IS phenomena instead of merely identifying the affordances of new technologies (Volkoff & Strong, 2017). The implementation of the methodological recommendations and meaningful application of the affordance concept were then demonstrated in qualitative studies aiming to explain the effective use of social (VR) applications in which users pursue shared versus different goals on the same platform. It has been shown that the effective use of social VR applications for collaborative learning is characterized by actualizing not only basic but also higher-level affordances that contribute to the achievement of the overarching shared goal of knowledge gain. The thesis adds to the scarce body of research on the influence of other users on effective use (Abouzahra & Ghasemaghaei, 2022; Wang & Nandhakumar, 2016) by showing that student peers can either have an encouraging or distracting influence on the actualization of higher-level affordances. By analyzing the effective use of social media for collective action as a contrasting context in which users pursue different goals on the same platform, the thesis answers the call for investigating the influence of external stakeholders on the successful actualization of affordances (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Sæbø et al., 2020). The study revealed that effective use in a context in which users pursue different goals on the same platform is characterized by dealing with constraints arising from interactions with other actors. While previous research has attributed the emergence of constraints primarily to technical limitations (e.g., Ciriello et al., 2019; Leonardi, 2011), this thesis contributes a novel perspective on the relationship between the affordance actualization of actors pursuing different goals and the emergence of constraints. It has been shown that actors can create constraints for themselves and other users depending on the way in which they actualize affordances (i.e., constructive versus provocative). This has implications for the affordance actualization process theorized by Strong et al. (2014), which so far does not consider the interaction between the actualization journeys of actors pursuing different goals and the impact of constraints on goal achievement. Furthermore, the findings have implications for the understanding of effective use, which has been conceptualized as successfully actualizing affordances contributing to goal achievement (Burton-Jones & Volkoff, 2017), since this thesis showed that dealing with constraints represents an equally important part of effective use.

6.2 Practical implications

The results of this thesis also have implications for practice. First, the proposed design principles can be applied by designers to implement VR and AR systems that enable effective use in higher education and emergency management. When designing VR applications for learning purposes, it should be noted that wearing a headset and practicing hands-on skills in front of fellow students without being able to see their reactions is perceived as uncomfortable by students. Therefore, VR systems in this context should be designed as social applications so that students share a common experience and are not perceived as disruptive observers. In the context of AR in crisis management, on the other hand, it is important to ensure that unfamiliar information visualization does not create additional cognitive load that prevents emergency operators from achieving their goals. The results provide detailed insights into the goals that users want to achieve in these contexts and through which design elements desired affordances can be made perceptible to support users in achieving their goals in the best possible way. A careful analysis of user goals and the affordances already provided by existing information systems is also recommended for the design of VR and AR systems intended to enable effective use in other contexts.

Second, this work involved the use of a social VR application over an entire semester, from which valuable recommendations can be derived for educators who wish to use VR effectively in teaching. The effective use of social VR applications for collaborative learning revolves around fostering enabling influence and reducing the distracting influence of other users. For example, educators could support the affordance actualization of students by pointing out rather hidden VR features and providing dedicated time in the first course session for affordance experimentation. To minimize the distracting influence of peer students, educators could establish clear guidelines such as that students should not play around with 3D objects when others are talking. It also helps to select a more serious virtual environment (e.g., an auditorium instead of a rooftop terrace) and work with smaller groups of students.

Third, this thesis provides practical implications for the effective use of social (VR) applications in contexts where actors pursue different goals on the same platform. It has been shown that actors pursuing different goals can create constraints for themselves and other actors through their way of affordance actualization. Although it can be an effective use strategy to prevent other actors from achieving their goals by creating constraints, it has been shown that this often has unintended consequences, which in turn, impede one's own goal achievement. It is therefore recommended that actors actualize affordances in a constructive way, guided by their goal achievement without explicitly intending to create constraints for other users.

6.3 Limitations and future research

The thesis is subject to the following limitations: The affordance-based design approach applied in the first part of this thesis assumes that users know what goals they want to achieve, and which affordances will help them to achieve these goals. However, there might be a difference between the goals users want to achieve and the goals they are expected to achieve. For instance, this could be the case in an educational context, in which lecturers define the learning goals for students, or in a corporate context, in which managers specify performance goals for employees. Furthermore, users might have a limited understanding of the affordances that can be provided by VR and AR systems, given that there are still many people who have never tried the technology before. For future research, it is thus recommended to not only involve users in an affordance-based design process but also involve actors who might specify the goals for them and technology experts who might have a better understanding of the affordances that can be provided. In addition, the design-oriented studies in the first part of this thesis evaluated conceptual or low-fidelity VR and AR prototypes, which might have limited the ability of respondents to identify affordances and constraints. Here, the evaluation of the proposed design principles based on functional prototypes could be an avenue for future research.

In the second part of this thesis, the affordance network approach has been applied, which is well suited to understanding the behavior that constitutes effective use in a specific context. However, this also means that the results might not be generalizable to other usage contexts. The affordance network approach does not consider social influences which have been shown to be relevant for the effective use of social (VR) applications. Also, the affordance network approach focuses only on the effective use of a single system (e.g., a social VR application) without considering that it might be used in combination with other systems (e.g., a learning management platform). Furthermore, the degree of goal achievement was measured based on the subjective assessments of the respondents. Here, future studies could include objective measurements of performance (i.e., effectiveness and efficiency) as indicators of goal achievement.

Future research on effective use from a technical affordance perspective could focus on how VR and AR systems can provide unique affordances in combination with other existing systems or emerging technologies. Such research would be important to avoid that VR and AR systems merely replicate affordances that could be better provided by other technologies and to make the unique action possibilities of VR and AR more perceptible to the user. Research from a socio-behavioral affordance perspective could tie in by adapting the affordance network approach in a way that considers how the affordances of multiple systems need to be actualized to achieve user goals, and thus effective use. This is crucial, as this thesis has shown that VR and AR systems should be designed as a supplement to existing systems rather than as a replacement. Future research could also consider the antecedents of effective use, such as personality traits or previous experience with VR and AR systems. Additionally, it could be investigated how hierarchy affects social influences on effective use. In an educational context, for instance, it might be conceivable that lecturers can influence effective use in a different way than student peers. Future research could also aim to extend the affordance actualization process by considering how actors pursuing different goals on the same social (VR) platform might create constraints for goal achievement. This would challenge the current assumption that individual affordance actualization journeys contribute in sum to an overarching organizational goal.

Furthermore, the rise of the metaverse as the ultimate open and interoperable 3D space will present exciting future research opportunities. Although current VR and AR applications offer various affordances for different user groups, they are separated from each other. The metaverse, on the other hand, is pictured as an interconnected web of virtual worlds where we will be living, working, shopping, learning, and much more (Weinberger, 2022). Currently, the meaning of the metaverse is still being shaped, and there are conflicting visions of different types of producers, such as big tech, non-commercial providers, and game producers, as well as users, such as individuals and companies (Dolata

& Schwabe, 2023). An affordance-based design approach could provide revelatory insights into the different goals these actors want to achieve and the affordances they desire from the metaverse which can then be translated into prescriptive design knowledge. This would provide information about whether users want to carry out all their everyday activities in the metaverse at all or which activities they still want to see anchored in physical reality. The results regarding the design of VR and AR systems in the context of this thesis already indicated that the potential of these technologies is seen in the interaction with existing information systems. With the shift from VR and AR applications for specific purposes toward a connected web of virtual worlds affording a wide variety of activities, it would be even more relevant to explore what constitutes effective use on platforms where users pursue different goals. As technology advances further, dealing with technical constraints becomes less relevant, while a better understanding of how to deal effectively with constraints that arise from interactions with other users is likely to become more important. Taken together, the metaverse is still a vision of the future; however, understanding the effective use of VR and AR as enabling technologies paves the path toward its implementation.

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Appendix

Paper 1: Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Paper 2: Fromm, J., Radianti, J., Wehking, C., Stieglitz, S., Majchrzak, T. A., & vom Brocke, J. (2021). More than experience? - On the unique opportunities of virtual reality to afford a holistic experiential learning cycle. *The Internet and Higher Education*, *50*, 100804. https://doi.org/10.1016/j.iheduc.2021.100804

Paper 3: Fromm, J., Eyilmez, K., Baßfeld, M., Majchrzak, T. A., & Stieglitz, S. (2021). Social media data in an augmented reality system for situation awareness support in emergency control rooms. *Information Systems Frontiers*, *25*, 303-326. https://doi.org/10.1007/s10796-020-10101-9

Paper 4: Fromm, J., Mirbabaie, M., & Stieglitz, S. (2020). A Systematic Review of Empirical Affordance studies: Recommendations for Affordance Research in Information Systems. *European Conference on Information Systems*.

Paper 5: Fromm, J., Stieglitz, S., & Mirbabaie, M. (forthcoming). Virtual reality in digital education: An affordance network perspective on effective use behavior. *The DATA BASE for Advances in Information Systems*, In Press. **This dissertation includes the pre-press version of the forthcoming article.**

Paper 6: Fromm, J., Stieglitz, S., & Mirbabaie, M. (2020). The Effects of Virtual Reality Affordances and Constraints on Negative Group Effects during Brainstorming Sessions. *Internationale Tagung Wirtschaftsinformatik*.

Paper 7: Stieglitz, S., Fromm, J., & Mirbabaie, M. (under review). Paradoxical Tensions Between Social Media Affordances and Constraints for Collective Action – Analysing the Interplay of Organisations Pursuing Different Environmental Policy Goals. *European Journal of Information Systems*. **This dissertation includes the author version submitted during the second revision round. The article is currently in the third revision round.**

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A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda

Jaziar Radianti [a], Tim A. Majchrzak [a,*], Jennifer Fromm [b], Isabell Wohlgenannt [c]

[a] University of Agder, Kristiansand, Norway
[b] University of Duisburg–Essen, Duisburg, Germany
[c] University of Liechtenstein, Vaduz, Liechtenstein

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ABSTRACT

Researchers have explored the benefits and applications of virtual reality (VR) in different scenarios. VR possesses much potential and its application in education has seen much research interest lately. However, little systematic work currently exists on how researchers have applied immersive VR for higher education purposes that considers the usage of both high-end and budget head-mounted displays (HMDs). Hence, we propose using systematic mapping to identify design elements of existing research dedicated to the application of VR in higher education. The reviewed articles were acquired by extracting key information from documents indexed in four scientific digital libraries, which were filtered systematically using exclusion, inclusion, semi-automatic, and manual methods. Our review emphasizes three key points: the current domain structure in terms of the learning contents, the VR design elements, and the learning theories, as a foundation for successful VR-based learning. The mapping was conducted between application domains and learning contents and between design elements and learning contents. Our analysis has uncovered several gaps in the application of VR in the higher education sphere—for instance, learning theories were not often considered in VR application development to assist and guide toward learning outcomes. Furthermore, the evaluation of educational VR applications has primarily focused on usability of the VR apps instead of learning outcomes and immersive VR has mostly been a part of experimental and development work rather than being applied regularly in actual teaching. Nevertheless, VR seems to be a promising sphere as this study identifies 18 application domains, indicating a better reception of this technology in many disciplines. The identified gaps point toward unexplored regions of VR design for education, which could motivate future work in the field.

1. Introduction

Digital devices are being increasingly adopted for learning and education purposes (Zawacki-Richter & Latchem, 2018). This can particularly be observed in the 1997–2006 period, when *networked computers for collaborative learning* were intensively used, and in the 2007–2016 period, when so-called *online digital learning* became widespread. During these two periods, people examined the

* Corresponding author.
E-mail addresses: jaziar.radianti@uia.no (J. Radianti), timam@uia.no (T.A. Majchrzak), jennifer.fromm@uni-due.de (J. Fromm), isabell.wohlgenannt@uni.li (I. Wohlgenannt).

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exploitation potential of emerging technologies, such as virtual learning environments (Boulton, Kent, & Williams, 2018; Muñoz-Cristóbal, Gallego-Lema, Arribas-Cubero, Martínez-Monés, & Asensio-Pérez, 2017), mobile devices (Wang, Wiesemes, & Gibbons, 2012), and computer-mediated communication (Mason & Bacsich, 1998). Recently, *virtual reality (VR) technologies* are actively being incorporated into education, teaching, and training in various application domains.

Although VR is not new, the recent developments in immersive technologies – in terms of visualization and interactions – have made VR increasingly attractive to scholars. The latest VR head-mounted displays (HMDs), such as HTC Vive or Oculus Rift, allow users to experience a high degree of *immersion*. Immersion describes the involvement of a user in a virtual environment during which his or her awareness of time and the real world often becomes disconnected, thus providing a sense of "being" in the task environment instead. Freina and Ott (2015) define this term as "a perception of being physically present in a non-physical world by surrounding the user of the VR system created with images, sound, or other stimuli" so that a participant feels he or she is actually "there".

Likewise, low-budget HMDs for mobile devices, such as Samsung Gear VR and Google Cardboard, enable *everyone* to experience immersive virtual environments. In addition, the current devices also offer interaction capabilities. While high-end VR equipment comes with dedicated controllers that support game play (e.g., Oculus Touch), low-budget HMDs, such as Google Cardboard, support gaze control or enable the user to interact with the virtual environment by providing a magnetic switch.

The HMD market is expected to be valued at USD 25 billion by 2022, growing at a Compound Annual Growth Rate of 39.52% between 2019 and 2025 (Global Augmented Reality, 2019). Therefore, the time is ripe to study immersive VR, primarily due to the increased capability of VR technology and reduced costs. For example, the recently released Oculus Quest comes in the form of a cordless HMD. While the design enables the user to move more freely, the cost is set at approximately 400 USD—pretty much the same price as the previous generation Rift with cables.

Moreover, VR has been described as the learning aid of the 21st century (Rogers, 2019). A study suggests that students retain more information and can better apply what they had learned after participating in VR exercises (Krokos, Plaisant, & Varshney, 2019). Considering the potential learning enhancement through VR use, it is understandable why researchers, organizations, and educators nowadays scrutinize this technology intensively, looking to add an extra dimension to the classroom with respect to both teaching and learning.

Due to the increasing scholarly attention paid to VR technologies, there are already a few comprehensive overviews and systematic mappings of VR applications for education (Jensen & Konradsen, 2018; Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014). For example, Merchant et al. (2014) focus on desktop VR in education while Jensen and Konradsen (2018) emphasize the application of HMD technologies. Although Jensen and Konradsen (2018) have a similar focus to this review, which is in terms of learning experience and learning outcome, they are not specific about their target audience (such as K12, higher education, vocational training, or job training). Besides, these two studies do not examine underlying learning theories governing the VR application development and the design elements of the VR applications.

Hence, in this paper, we focus on the use of immersive VR in higher education and answer the following questions:

- How are immersive VR technologies embedded into higher education?
- What design elements, learning contents, and immersive technologies have been laid out to support VR-based learning?
- What learning theories have been applied to guide VR application design and development for higher education?
- What evaluation methods have been employed to evaluate the learning outcomes?
- What higher education domains have applied VR to teaching and learning?

In this article, we carry out a systematic mapping of the existing VR literature and highlight the immersive aspect of VR to answer these questions, which are presented in detail in Table 2. Our aim is to contribute to the extant body of knowledge on the application of digital devices for educational purposes.

This work is organized as follows: In Section 2, related works on systematic reviews of VR in an educational context are presented. The section concludes with a gap analysis and an explanation of how our work addresses the noted gaps. Then, our research design is described in Section 4, including our literature identification search procedure, our semi-automatic filtering process, and analysis methods. In Section 5, four analysis frameworks (*1. research design*, *2. research method and data analysis*, *3. learning*, and *4. design element*) and their sub-frameworks are formulated as an overarching category foundation for the consolidation and analysis of the results. Drawing on this classification, we identify patterns of VR design element use for specific learning contents in higher education. The results are discussed in Section 6 to highlight the implications, opportunities for future research, recommendations for lecturers, and limitations of our work. Finally, we draw a conclusion in Section 7. Three appendices (from p. 32) provide more detailed information about certain aspects of our research design as well as a list of articles included in our literature study.

2. Theoretical background

In this section, we draw the background of the two main topics combined in this paper: immersive VR and learning theories. Bringing these topics together allows us to analyze the usage of VR in the higher education context.

2.1. VR and immersion

VR can be defined as "the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment" (Biocca & Delaney, 1995). Immersion, presence, and interactivity are regarded as the core characteristics of VR technologies (Ryan, 2015; Walsh & Pawlowski, 2002). The term *interactivity* can be described as the degree to which a user can modify the VR environment in real-time (Steuer, 1995). *Presence* is considered as "the subjective experience of being in one place or environment, even when one is physically situated in another" (Witmer & Singer, 1998). While researchers largely agree on the definitions of interactivity and presence, differing views exist on the concept of *immersion*. One branch of researchers suggests that immersion should be viewed as a *technological* attribute that can be assessed objectively (Slater & Wilbur, 1997), whereas others describe immersion as a subjective, individual belief, i.e., a *psychological* phenomenon (Witmer & Singer, 1998).

Jensen and Konradsen (2018) suggest an additional perspective concerning the positive effects of immersion and presence on learning outcomes. The results of the reviewed studies in their work show that learners who used an immersive HMD were more engaged, spent more time on the learning tasks, and acquired better cognitive, psychomotor, and affective skills. However, this study also identifies many factors that can be reinforcers or barriers to immersion and presence. Both graphical quality of VR and the awareness when using VR, for instance, can reduce the sense of presence. Individual personality traits may also be associated with a limited acquisition of skills from using VR technologies.

According to the technological view, the term immersion means the "extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality" (Slater & Wilbur, 1997). More precisely, this includes the degree to which the physical reality is excluded, the range of sensory modalities, the width of the surrounding environment as well as the resolution and accuracy of the display (Slater & Wilbur, 1997). The technological attributes of a VR technology – such as the frame rate or the display resolution – consequently determine the degree of immersion that a user experiences (Bowman & McMahan, 2007). In contrast, the psychological point of view considers immersion to be a psychological state in which the user perceives an isolation of the senses from the real world (Witmer & Singer, 1998). According to this view, the perceived degree of immersion differs from person to person and the technological attributes barely influence it (Mütterlein, 2018).

With our systematic mapping study, we aim to identify the current applications of immersive VR in higher education. For this reason, we set specific inclusion and exclusion criteria to distinguish papers that describe immersive VR applications from papers that describe non-immersive VR applications. As the subjective experience of immersion could hardly be used as a selection criterion, we defined certain types of VR technologies as either immersive or non-immersive based on their technological attributes. These specific technology types were then used as either the inclusion or exclusion criteria. For this paper, we considered *mobile VR* (e.g., Google Cardboard, Samsung Gear), *high-end HMDs* (e.g., Oculus Rift, HTC Vive), and *enhanced VR* (e.g., a combination of HMDs with data gloves or bodysuits) as immersive.[1] These VR technologies allowed the user to fully immerse into the virtual environment (Khalifa & Shen, 2004; Martín-Gutiérrez, Mora, Añorbe Díaz, & González-Marrero, 2017). Desktop VR and Cave Automatic Virtual Environment (CAVE) systems, however, were considered as *non*-immersive because the user can still recognize the screen or a conventional graphics workstation (Biocca & Delaney, 1995; Robertson, Czerwinski, & Van Dantzich, 1997).

2.2. Learning paradigms

An understanding of the existing learning paradigms is essential for performing an analysis of the current state of VR applications in higher education. Thus, we introduce the main ideas behind the existing learning paradigms. Literature distinguishes between behaviorism, cognitivism, and constructivism (Schunk, 2012). Other scholars also include experiential learning (Kolb & Kolb, 2012) to this list and, recently, connectivism has been introduced as a new learning paradigm (Kathleen Dunaway, 2011; Siemens, 2014). Each learning paradigm has developed various theories about educational goals and outcomes (Schunk, 2012). Each of these theories also offers a different perspective on the learning goals, motivational process, learning performance, transfer of knowledge process, the role of emotions, and implications for the teaching methods.

Behaviorism assumes that knowledge is a repertoire of behavioral responses to environmental stimuli (Shuell, 1986; Skinner, 1989). Thus, learning is considered to be a passive absorption of a predefined body of knowledge by the learner. According to this paradigm, learning requires repetition and learning motivation is extrinsic, involving positive and negative reinforcement. The teacher serves as a role model who transfers the correct behavioral response.

Cognitivism understands the acquisition of knowledge systems as actively constructed by learners based on pre-existing prior knowledge structures. Hence, the proponents of cognitivism view learning as an active, constructive, and goal-oriented process, which involves active assimilation and accommodation of new information to an existing body of knowledge. The learning motivation is intrinsic and learners should be capable of defining their own goals and motivating themselves to learn. Learning is supported by providing an environment that encourages discovery and assimilation or accommodation of knowledge (Shuell, 1986),RN23. Cognitivism views learning as more complex cognitive processes such as thinking, problem-solving, verbal information, concept formation, and information processing. It addresses the issues of how information is received, organized, stored, and retrieved by the mind. Knowledge acquisition is a mental activity consisting of internal coding and structuring by the learner. Digital media, including VR-based learning can strengthen cognitivist learning design (Dede, 2008). Cognitive strategies such as schematic organization, analogical reasoning, and algorithmic problem solving will fit learning tasks requiring an increased level of processing, e.g. classifications, rule or procedural executions (Ertmer & Newby, 1993) and be supported by digital media (Dede, 2008).

[1] It should be noted that immersion apparently has a sociocultural aspect the notion of which changes over time. When the first 3D games were introduced in the early 1990s, players would consider these to be *immersive* despite seeing software-rendered graphics in a resolution of 320X160 pixels with 2D sprites, often displayed on a small CRT monitor.

Constructivism posits that learning is an active, constructive process. Learners serve as information constructors who actively construct their subjective representations and comprehensions of reality. New information is linked to the prior knowledge of each learner and, thus, mental representations are subjective (Fosnot, 2013; Fosnot & Perry, 1996). Therefore, constructivists argue that the instructional learning design has to provide macro and micro support to assist the learners in constructing their knowledge and engaging them for meaningful learning. The macro support tools include related cases, information resources, cognitive tools, conversation, and collaboration tools, and social or contextual support. A micro strategy makes use of multimedia and principles such as the spatial contiguity principle, coherence principle, modality principle, and redundancy principle to strengthen the learning process. VR-based learning fits the constructivist learning design (Lee & Wong, 2008; Sharma, Agada, & Ruffin, 2013). Constructivist strategies such as situated learning, cognitive apprenticeships, and social negotiation are appropriate for learning tasks demanding high levels of processing, for instance, heuristic problem solving, personal selection, and monitoring of cognitive strategies (Ertmer & Newby, 1993).

Experientialism describes learning as following a cycle of experiential stages, from concrete experience, observation and reflection, and abstract conceptualization to testing concepts in new situations. Experientialism adopts the constructivist's point of view to some extent—e.g., that learning should be drawn from a learner's personal experience. The teacher takes on the role of a facilitator to motivate learners to address the various stages of the learning cycle (Kolb & Kolb, 2012).

Connectivism takes into account the digital-age by assuming that people process information by forming connections. This newly introduced paradigm suggests that people do not stop learning after completing their formal education. They continue to search for and gain knowledge outside of traditional education channels, such as job skills, networking, experience, and access to information, by making use of new technology tools (Siemens, 2014).

Of course, there are many varieties of learning theories in addition to the main paradigms listed here, such as those developed based on the information processing theory or the social cognitive theory. Regardless of which learning theories under each paradigm are used by VR researchers, it is crucial that the development of VR applications for higher education is firmly grounded on existing learning theories because learning theories offer guidelines on the motivations, learning process and learning outcomes for the learners.

3. Related work

In the following section, we first present an overview of literature reviews before discussing the gaps found in existing works.

3.1. Literature reviews

In our search for existing systematic reviews and mapping studies on VR in an educational context, the Scopus digital library returned 59 peer-reviewed articles published between 2009–2018, which included search terms "virtual reality" and "systematic review" in their titles and were linked to *education*, *training*, *teaching*, or *learning*. The most popular application domains covered in these systematic reviews were medicine (78%), social science (15%), neuroscience (11%), and psychology (11%). We filtered the search results further by checking the abstracts of these studies for whether the immersion aspect was also included in them.

We found 18 potentially relevant articles, of which four were very relevant for our work and reported the results of a systematic mapping study. In addition, we found two other thematically relevant articles, one of which described a review and one a meta analysis. Hence, we examine six review articles in total and introduce them shortly to illustrate the research gap we address with our systematic mapping study.

Feng, González, Amor, Lovreglio, and Cabrera-Guerrero (2018) conducted a systematic review of immersive VR serious games for evacuation training and research. The application area was quite specific, i.e., building evacuation and indoor emergencies. The authors proposed the use of serious games, as these have increasingly been adopted for pedagogic purposes. Feng et al. (2018) focused on examining immersion through a virtual environment, where the participants could feel that they are physically inside the artificially simulated environment. The authors identified the pedagogical and behavioral impacts, the participants' experience as well as the hardware and software systems that were used to combine serious games and immersive VR-based training. They reported several pedagogical and behavioral outcomes, which included knowledge of evacuation best practices, self-protection skills, and spatial knowledge. The typical methods used for measuring the learning outcomes in this study were questionnaires, open-ended question interviews, paper-based tests, and logged game data (e.g., evacuation time, damage received). Regarding behavioral impacts, the following points were specified:

- Evacuation facility validation (tested and validated different evacuation facility designs and installations),
- Behavioral compliance (investigated whether participants followed the evacuation instructions),
- Hazard awareness (investigated whether participants could notice hazards in the environment),
- Behavioral validation (validated the hypothetical behavior model),
- Social influence (examined the social influence on evacuation behavior),
- Behavior recognition (identified different behaviors under different evacuation conditions), and
- Way-finding behavior (studied evacuation way-finding behavior).

Participants were observed as to whether they showed fear, engagement, stress, and high mental workload during the training. To track these experiences, the researchers employed an electrodermal activity sensor to evaluate fear and anxiety, a photoplethysmography sensor to obtain blood volume pulse amplitude, and a multichannel physiological recorder to measure the emotional responses of participants. Feng et al. (2018) also mentioned the characteristics of the game environments identified during the study, i.e., the teaching methods through direct or post-training feedback, navigation, static and dynamic hazard simulation, narratives – such as action, performance or instruction-driven, interactivity/non-interactivity with non-playable characters – as well as audio-visual and motion sense stimulation.

Wang, Wu, Wang, Chi, and Wang (2018) specifically surveyed the use of VR technologies for education and training in the construction engineering field. The authors focused on VR technologies, applications, and future research directions. The study found five major technology categories used in the construction engineering context—desktop VR, immersive VR, 3D game-based VR, building information modeling VR, and augmented reality. The authors noted that desktop VR was used to improve the students' motivation and comprehension. Under immersive VR, the authors subsumed HMDs combined with sensor gloves and suits, the so-called virtual structural analysis program and CAVE systems, where the immersive virtual environment is formed around the user's location by using a 3D immersive VR power wall. Wang et al. (2018) concluded that immersive VR was important for improving concentration and giving trainees a measure of control over the environment. Building information modeling VR has been applied in construction engineering to visualize schedule information and construction work on site, enabling students to interact with building elements in a VR environment, and a system that includes a question-and-answer game to enhance the learning experience. The authors found that VR applications are mostly used in architectural visualization and design education, construction safety training, equipment and operational task training, and structural analysis education. In addition, Wang et al. (2018) revealed five future directions for VR-related education in construction engineering:

- Integrations with emerging education paradigms,
- Improvement of VR-related educational kits,
- VR-enhanced online education,
- Hybrid visualization approaches for ubiquitous learning activities, and
- Rapid as-built scene generation for virtual training.

Chavez and Bayona (2018) looked at VR in the learning context and examined the characteristics that determine successful implementation of this technology as well as its positive effects on learning outcomes. The authors defined 24 characteristics of VR—e.g., interactive capability, immersion interfaces, animation routines, movement, and simulated virtual environment. They discovered that, in certain subjects such as medicine, the "movement" feature is vital for learning about the reaction of a person's body, whereas, in general education, the "immersion interfaces" are often used as a way to learn through "live experience" that is closer to reality. The authors further specified 17 positive effects of VR, including improving learning outcomes, living experiences that are closer to reality, intrinsic motivation, increasing level of interest in learning, and improved skills, although in some fields, such as psychology, no meaningful learning effects were observed.

To some extent, there are similarities between this work and our work; however, clear differences can be identified. First, we specifically focus on immersive HMDs as recent technology developments, while Chavez and Bayona (2018) did not distinguish between immersive and non-immersive VR. Second, we use a systematic mapping method to reveal what VR design elements have been used for teaching different types of learning content, such as declarative knowledge or procedural and practical knowledge. In contrast, Chavez and Bayona (2018) analyzed the characteristics of VR applications on a more abstract level and mapped these using broad application domains such as medicine or psychology.

Suh and Prophet (2018) discussed the state of immersive VR research in their systematic study and, in particular, named current research trends, major theoretical foundations, and research methods used in previous immersive technology research. Regarding research trends, Suh and Prophet (2018) found four popular domains that use immersive technologies: education, entertainment, healthcare, and marketing. They also identified two main research streams. First, studies that examine the user experience and the effects of unique system features of immersive technology. Second, research that scrutinizes how the use of immersive technologies enhances user performance through, for instance, learning and teaching effectiveness, task performance, and pain management. With respect to the theoretical foundations employed in existing immersive technology studies, these authors further identified the flow theory, conceptual blending theory, cognitive load theory, constructive learning theory, experiential theory, motivation theory, presence theory, situated cognitive theory, media richness theory, stimulus–organism–response model, and the technology acceptance model. In terms of the research method, experiments, surveys, and multi-method approaches were frequently used. Suh and Prophet (2018) provided the following classification framework for immersive technology use:

- Stimuli aspect (i.e., sensory, perceptual, and content),
- Organism aspect (i.e., cognitive and affective reactions),
- Response aspect (i.e., positive and negative outcomes), and
- Individual differences in VR use (i.e., gender, age, sensation-seeking tendency, and personal innovativeness).

Jensen and Konradsen (2018) reviewed the use of HMDs in education and training for skill acquisition. The authors examined factors influencing immersion and presence for applying VR for education, the influence of immersion and presence on learning, and situations where HMDs are useful for cognitive, psychomotor and affective skills acquisition. They also studied physical discomfort due to HMD usage and learners' attitudes toward HMDs. The authors stressed the importance of the content, e.g. simulations as learning enablers rather than the HMD itself. Some barriers of using HMDs in education and training were identified, i.e. lack of content and the designs of the HMDs which are more entertainment-oriented than education-oriented. To be relevant for teachers, HMDs should possess user content editing capability.

Table 1
Summary of systematic reviews on VR technologies in an educational context.

Authors	Database source	Keywords search	# Articles and timespan	Focus
Feng et al. (2018)	Scopus, Engineering Village	Virtual reality, VR, virtual environment, virtual simulation	15 out of 567, no time constraint	Indoor building evacuation, pedagogical and behavioral impacts, gaming environment development and outcome, participant experience measures
Wang et al. (2018)	Scopus, Web of Science	Virtual reality, virtual environment, augmented reality, 3D, game	66 out of 347, years 1997–2017	VR and VR-related technologies, their applications, implementation areas, and future directions for construction engineering education and training
Chavez and Bayona (2018)	IEEE Xplore Digital, Science Direct, PsycINFO, Wiley Online Library, ACM Digital Library, Blackwell Publishing, and Google Scholar	Virtual reality, VR, serious game, virtual environment, VE, decision making, influence, education, higher education, professional education, not augmented reality	30 out of 4 060, years 1999–2017	The characteristics of VR, teaching subjects and outcomes of VR implementation into the learning process
Suh and Prophet (2018)	Scopus, Social Sciences Citation Index (SSCI)	Immersive technology, augmented reality, virtual reality, mixed reality	54 out of 926, years 2010–2017	Trends, theoretical foundations and research methods in immersive technology research
Jensen and Konradsen (2018)	Scopus, Web of Science, EBSCOhost, PubMed, IEEE Xplore, ERIC, PsycINFO, IBSS	Virtual reality, head-mounted display, education, training, learning.	21 out of 8 185, 2013–2017	Skill acquisition (psychomotor, cognitive and affective); documentation of experimental or quasi-experimental studies.
Merchant et al. (2014)	PsycINFO (EBSCO), Medline (Pub Med), Dissertation and Thesis, Eric (EBSCO), Education Full Text, PaperFirst, CINHAL, Manual search in some journals, Google Scholars	Virtual reality, virtual worlds, virtual learning environments, computer assisted learning, AI, mixed reality, synthetic environment, virtual classrooms, augmented reality, immersive learning environment, computer games, game-based learning environment, serious games, simulations; education, learning, instruction, and instructional design	67 out of 7 078, all studies until 2011	Desktop-based virtual reality technologies as an assessment, diagnostic, or therapeutic tool; games, simulations or virtual worlds

Despite the focus on immersive VR technologies, the study of Jensen and Konradsen (2018) is still different from ours in several points: First, the work does not analyze immersive VR applications in terms of learning content, design elements, underlying learning theories, and the VR application domains. Second, the findings are limited to declarative knowledge, gesture skills, and emotional control while our study considers other types of learning outcomes as well.

Merchant et al. (2014) conducted a meta-analysis to address the impact of instructional design principles for VR-based instructions. They pointed out improved learning outcomes through games compared to simulations and virtual worlds, but there was an inverse relationship between the number of treatment sessions and learning outcome gains. On the contrary, virtual worlds deteriorate students' learning outcome gains. In simulation studies, the elaborated explanation feedback type is more suitable for declarative tasks whereas knowledge of the correct response is more appropriate for procedural tasks.

We identified distinct contributions compared to our study. First, the review looks at both K-12 and higher education settings. Second, it examines desktop VR technologies that are excluded in our study. Third, the authors examined the suitability of particular VR instruction designs for certain learning outcomes. In other words, our study will be complimentary with the findings of the work of Merchant et al. (2014).

The aspects covered in systematic reviews are summarized in Table 1.

3.2. Gaps in the systematic review of VR for education literature

In order to make a contribution to theory, our study aims to fill gaps in existing literature.

Immersion: Suh and Prophet (2018) focused on immersive VR in their systematic review. However, they also examined several different application areas besides education, such as health care and marketing. Thus, in this article, immersive VR applications in the education field were not discussed in-depth. Likewise, the review by Merchant et al. (2014) stresses the learning outcomes. The review of Feng et al. (2018) only considered serious games as a specific type of immersive VR applications. In contrast, Chavez and Bayona (2018) did not look at immersive VR in particular but rather examined the characteristics of VR in general. Wang et al. (2018) discussed immersive VR among other related technologies, such as non-immersive VR (i.e., desktop VR) and augmented reality. Jensen and Konradsen (2018) do not analyze immersive VR from the perspective of learning content, design elements, underlying learning theories, and the VR application domains.

Table 2
Research Questions of this study.

#	Research Question (RQ)
RQ1	What types of immersive VR technologies are used in higher education?
RQ2	Which research designs, data collection methods, and data analysis methods are applied to examine the use of immersive VR in higher education?
RQ3	What learning theories are applied to examine the use of immersive VR in higher education?
RQ4	Which research methods and techniques are applied to evaluate the learning outcomes of immersive VR usage in higher education?
RQ5	In what higher education application domains are immersive VR applications used?
RQ6	For which learning contents in higher education are immersive VR applications used?
RQ7	What design elements are included in immersive VR applications for higher education?
RQ8	What is the relationship between application domains and learning contents of immersive VR applications for higher education?
RQ9	What is the relationship between learning contents and design elements of immersive VR applications for higher education?

Application areas of VR-based education: While some existing systematic reviews focused on a very specific application area such as construction engineering (Wang et al., 2018) or evacuation training (Feng et al., 2018), others considered education only as *one* application area among many (Suh & Prophet, 2018). The work of Chavez and Bayona (2018) provided an overview of VR application areas in education but can be distinguished from our work through other aspects (i.e., the focus on immersive VR). Merchant et al. (2014) analyze the literature that is based on the desktop VR technologies.

Overview of teaching content: In addition to the gaps described earlier, all six reviews considered only broad VR application domains in education (i.e., medicine or psychology) but did not shed light on specific types of learning content that can be taught using VR applications (e.g., declarative knowledge or procedural and practical knowledge).

Design elements: While Chavez and Bayona (2018) analyzed the characteristics of VR in an educational context on a more abstract level, the other five reviews did not focus on the design elements underlying the content of HMD-based teaching and education. Furthermore, a mapping of VR design elements that are used for teaching specific types of learning content is missing thus far. Merchant et al. (2014) address a single design principle, i.e. instruction design.

Methods and theories: Suh and Prophet (2018) provided an overview of research methods and theories applied in immersive technologies research but did not particularly focus on education. The other existing reviews focused on entirely different aspects such as application domains. Thus, an overview of the learning theories that are used as a theoretical foundation for studies on VR-based learning is still missing.

Evaluation: Little knowledge has been accumulated on how to evaluate learning outcomes when using VR in teaching activities. While Feng et al. (2018) collected methods for measuring the learning outcomes in the specific application area of evacuation training, the other existing reviews did not consider learning outcome evaluation methods. Even though the technology being reviewed was desktop VR, Merchant et al. (2014) discusses the number of treatment sessions and feedback mechanism as factors affecting the learning outcome. However, the applicability of these treatments for immersive VR needs further examination.

4. Research design

In the following section, we describe our research design, which consists of the method, review process, and classification framework.

4.1. Research method and research questions

Consensus about the design space of VR-based teaching would significantly aid future developments. To this end, we apply a systematic mapping approach to the literature by extracting key information from documents indexed in four scientific digital libraries. Our research aims to obtain an overview of the relationship between application domains and learning contents and also between design elements and learning contents. Based on our results, we propose an agenda for future research and first recommendations for the future development of VR applications for higher education.

Systematic literature reviews, as proposed by Kitchenham et al. (2009) or Webster and Watson (2002), have been widely used as an approach to obtain comprehensive insights into a specific research domain. Furthermore, to answer questions about the structure of a broad field, relevant topics within this field, as well as research trends, Kitchenham et al. (2009) recommend using a mapping study, which is a specific form of a systematic literature review. In contrast to a standard systematic literature review, which is driven by a particular research question, Kitchenham et al. (2009) point out that a mapping study reviews a broader topic and classifies the primary research papers within the specific domain under study. The research questions suggested in such a study have a high level of abstraction and include issues such as: what sub-topics have been discussed, what empirical methods have been used, and what sub-topics have adequate empirical studies to support a more detailed systematic review. An example of applying the mapping study approach to a literature review is the work of Wendler (2012).

To accomplish the objective of this study, we propose several research questions that focus on systematizing and structuring the research on VR applications for higher education. They are listed in Table 2.

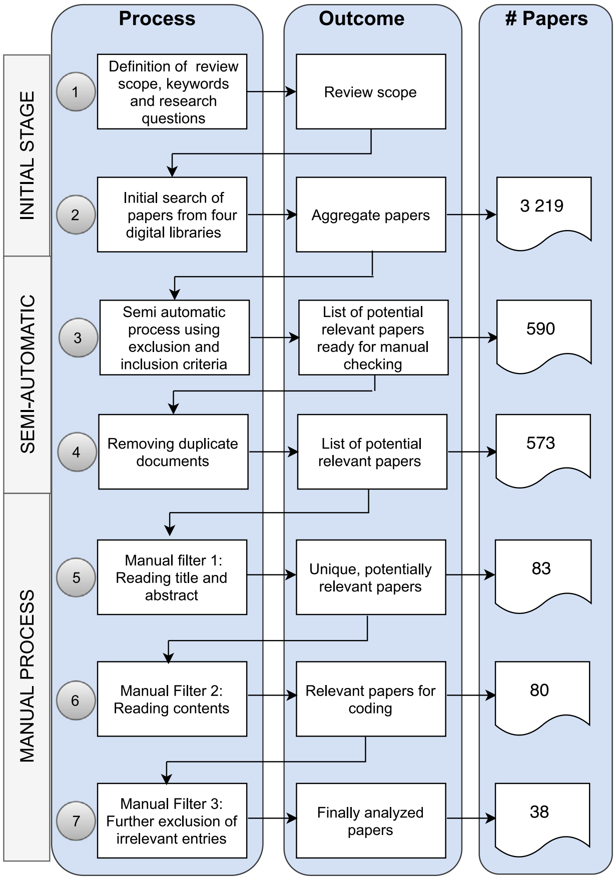

Fig. 1. Review process.

4.2. Review process and literature search method

Our review process included procedures, considerations, and decisions that lead to a consolidated list of articles to be reviewed in-depth. We conducted a systematic mapping study, as suggested by Wendler (2012), to obtain an overview of the field. The overall review process, from defining the review scope to identifying a final selection of articles for analysis, is illustrated in Fig. 1. In total, the article review process consisted of seven steps.

4.2.1. Definition of the review scope, keywords, and research questions (step 1)

While the research questions have been described in Table 2, defining the scope and keywords was quite challenging because, in fact, VR research is extensive and the number of publications in this area is abundant. We followed the procedures, as suggested by Webster and Watson (2002), starting by selecting keyword search strategies in relevant digital libraries. These relevant libraries for our search were the IEEE Xplore Digital Library, ProQuest, Scopus, and Web of Science. IEEE Xplore is a rich repository that covers the domains of computer science, information technology, engineering, multimedia, and other software-related publications. ProQuest comprises articles in the areas of medicine, surgery, and nursing sciences. Scopus provides a wide range of publication domains, covering the fields of technology, natural sciences, information technologies, social sciences, and medicine. The Web of Science indexes social science, arts, and humanities spheres. We were aware of other databases, such as the ACM digital library, Science Direct, JSTOR, EBSCO, and Taylor & Francis, but we expected most of the articles they contain to already be a part of the databases we selected. This expectation was confirmed by exemplary cross-checks.

4.2.2. Initial paper search in four digital libraries (step 2)

For our database search, we defined the following search string[2]:

[2] Appendix A (p. 32) gives the search strings used for each database.

```
"virtual reality" OR VR
AND educat* OR learn* OR train* OR teach*
AND "higher education" OR university OR college
AND NOT "machine learning" OR "deep learning" OR "artificial intelligence" OR "neural network"
AND NOT rehabilitation OR therapy
```

Specifying `''higher education'' OR university OR college` was crucial in order to minimize irrelevant application areas, such as VR for primary, secondary, or vocational education. By adding these keywords, we reduced the results of one database from more than 3 000 articles to approximately 800 articles. The term `NOT (''machine learning'' OR ''deep learning'' OR ''artificial intelligence'' OR ''neural network'')` was added to avoid articles that reported on artificial intelligence without the (human) learning context. In addition, the keywords `rehabilitation` and `therapy` were often associated with physical training, which was also out of scope. The exclusion keywords were obtained after conducting several search tests, followed by a thorough examination of the results.

The search results covered peer-reviewed scientific journal articles and conference papers written in English and published between 2016 and 2018. A Google Trends search revealed an increasing interest in the topic of VR since 2016, when the immersive HTC Vive headset was released. Thus, starting the search from 2016 increased the likelihood of obtaining immersive VR-based learning articles. Due to the novelty of immersive HMDs, the inclusion of conference papers was necessary, as the majority of innovative research and development using HMDs was being documented in conference papers instead of journal articles. The aggregated results of the initial search were 3 219 articles. Since we dealt with a considerable number of results, we implemented a two-stage filtering process: (1) semi-automatic filters for the exclusion and inclusion criteria and (2) manual filters to identify potential papers.

4.3. Semi-automatic process

Steps 3 and 4 in Fig. 1 were semi-automatic processes created to exclude and include articles by checking and extracting a list of the most critical words and word clusters from the abstracts. We made use of the list to manually select representative exclusion and inclusion keywords to narrow down the list of articles to review. The goal of this process was to ensure that the articles about immersive VR technologies were appropriately captured.

4.3.1. Exclusion and inclusion method (step 3)

First, we performed a content analysis of all databases using KH Coder 3 that can be used for quantitative content analysis, text mining, and computational linguistic purposes (Coder, 2017). To conduct this analysis, pre-processing was performed by removing punctuation marks, such as periods, commas, and question marks. Stop words (e.g., and, or, of), which provide no additional meaning to a sentence, were also removed. The words with conjugated or inflected forms, such as verbs or adjectives, were reduced to their word stems. For instance, *buy*, *bought*, and *buying*, in a given text, would all be extracted as *buy*. We conducted further pre-processing by only including nouns, proper-nouns, and verbs in the analysis, while ignoring prepositions, adjectives, and adverbs, before conducting word clustering.

KH Coder 3 usage was intended for extracting the collections of articles' abstracts into word clusters and not in order to conduct complete computational linguistics-based content analysis. The tool provides *TermExtract*, which is a feature that automatically extracts clusters of words that often occur together—e.g., "virtual spatial navigation". It could happen that the same word is clustered into two clusters, such as "virtual spatial" and "navigation", or that unintended cluster of words emerge. However, each word cluster was scored and, therefore, the highly scored clusters were deemed to be reliable (see Higuchi (2016) for technicalities of KH Coder 3). Thus, this process is entirely different from simply extracting a frequency word list, where each extracted word is ranked based on the frequency of its occurrence.

This process returned a list of word clusters with scores and we used the 1 000 most important words and clusters that resulted from this process to manually select the *good enough* keywords for additional exclusions and inclusions. This process led to a reduced selection of potentially relevant articles, which had to be marked as "relevant" and "not relevant" during the subsequent manual process.

It should be noted that we could have applied more straightforward filtering criteria, such as the number of citations, e.g., to only review papers that received at least twenty citations. However, this would not have been an ideal approach because we might have overlooked or excluded interesting, relevant, recent papers due to a small number of citations. It should be recalled that most collected papers were relatively newly published (between 2016 and 2018).

Second, we went through the list of extracted words and clusters to identify the terms that were useful as additional exclusion and inclusion criteria. Exemplary exclusion words were "augmented reality" and "desktop virtual reality" because we only focused on immersive VR and not on augmented or mixed reality. Certain terms, such as "primary education", "secondary education", and "vocational education", were also noticeable exclusion terms because we only focused on higher education. An exhaustive list of exclusion words is documented in Appendix B (p. 32).

The following inclusion keywords were selected:

```
vr application, headset, glasses, goggles, immersive, immersion, immers, head-mounted display,
head mounted display, oculus, vive, samsung gear, google cardboard, playstation vr,
playstation virtual reality, pimax, google daydream, samsung odyssey.
```

Table 3
Semi-automatic filtering results and manual checking.

Source	Original	Semi-automatic		Manual checking	
		Exclusion	Inclusion	Duplicate	Abstract
IEEE Explore	1 656 articles	899 articles	345 articles	340 articles	35 articles
ProQuest	877 articles	494 articles	168 articles	167 articles	10 articles
Scopus	574 articles	374 articles	60 articles	54 articles	30 articles
Web of Science	112 articles	97 articles	17 articles	12 articles	5 articles
Total	3 219 articles	1 864 articles	590 articles	573 articles	80 articles

These keywords were selected to ensure that our search would return papers that dealt with immersive VR technologies such as HMDs. It should be noted here that, even though we applied a semi-automatic approach at this stage, we performed quality checks by skimming the abstracts to check whether the excluded papers were truly irrelevant.

The word extraction and selection was conducted for each database separately because the results from each database varied significantly. For example, the IEEE database often returned computer science-related articles, while the papers indexed in ProQuest were mostly related to medicine, health, and nursing sciences. These keyword selections were performed by all authors in order to agree on the choices of the inclusion and exclusion terms and to clarify if disagreements occurred.

4.3.2. Removing duplicate documents (step 4)

Duplication check was a rather straightforward process. ProQuest, for instance, consists of multiple databases and sometimes returns two identical articles. By activating ProQuest's automatic removal feature, redundant results were reduced. In this manner, 28 out of 905 articles were purged from ProQuest so that the number of identified articles was reduced to 877. The duplication check of the articles across the databases was done using title-based sorting in an Excel spreadsheet. The aggregated results, after the implementation of the semi-automatic process and duplication removal, were 590 articles, as summarized in Table 3.

4.4. Manual selection process

This process was comprised of three steps—reading the titles and abstracts, reading the contents, and further exclusion of irrelevant articles.

4.4.1. Manual filter 1: Reading the titles and abstracts (step 5)

In step 5, all authors read through the 590 abstracts obtained from the semi-automatic process, marking the articles as either relevant or not relevant. To increase the judgment reliability at this stage, each abstract was read by at least two authors. If there were disagreements, the remaining two authors would also judge the abstracts. This process resulted in 83 articles ready for further processing. The summary of the papers, from the semi-automatic process to the list of articles ready for thorough reading, can be seen in the rightmost column of Table 3.

4.4.2. Manual filter 2: Reading the contents (step 6)

This second manual stage not only served as a filtering process but also as a pre-coding stage. As the coding process involved all authors (four persons), there was a risk that we would code and judge the articles differently. To increase the intercoder reliability of the coding process and to assure that all paper reviewers worked uniformly, all four authors took part in a coding test with twenty selected papers. At this stage, we compared the results and discussed discrepancies in the way we coded the articles until we reached consensus, instead of calculating the discrepancies quantitatively as suggested by Krippendorff (2004) or Holsti (1969). To help the reviewers judge the category of the paper content in a similar way, we added definitions and explanations for each concept that were likely to be a subject of multiple interpretations. At this cross-validation stage, the list of "ready-to-code" papers was already reduced to 80 articles.

4.4.3. Manual filter 3: Further exclusion of irrelevant entries (step 7)

During this stage, we started the actual coding process and continuous reading through all papers allowed irrelevant articles to be further discarded. We continued practicing the intercoder reliability process in which each paper was coded by two persons. Any discrepancies were discussed until we had a set of articles with agreed coding categories ready. In the end, we included 38 relevant articles into our systematic mapping study. They are listed in Appendix C (p. 32).

4.5. Classification framework for analysis

Before beginning the coding process, we developed a *concept matrix*, as suggested by Webster and Watson (2002), to allow us to identify the learning contents, application domains, and VR design elements in relation to VR-based education. The analysis followed five steps, as can be seen in Fig. 2. A slight overlap with the third stage of the manual filtering papers exists, as manual filtering and coding were performed simultaneously. The concept matrix was a prerequisite to conducting a third manual filtering.

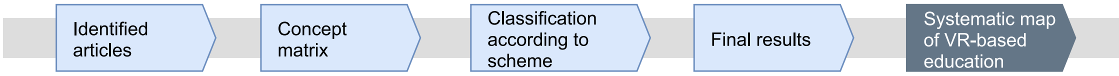

Fig. 2. Classification stages.

Table 4
Definition of the categories.

Categories	Explanation
Empirical, qualitative research	A study that adopts well-established qualitative methodology (Creswell & Creswell, 2017), such as narrative research, phenomenology, grounded theory, ethnography, and case studies.
Empirical, quantitative research	A study that includes elements such as true experiments, with random assignment of subjects to treatment conditions, and less rigorous experiments such as quasi-experimental and correlational approaches. This type of study can also consist of a survey that includes cross-sectional and longitudinal studies using questionnaires (Creswell & Creswell, 2017).
Conceptual	A study that is designed with a specific focus on theoretical advancements (Stolterman & Wiberg, 2010).
Design-oriented	A study that is intended to reveal new knowledge as its primary objective. This is particularly the case if this knowledge is such that it would not have been attainable if the design – the bringing forth of an artifact (e.g., a research prototype) – had not been a crucial element of the research process (Fallman, 2003).
No method explained	A study does not have a recognizable method at all.

4.5.1. Coding

The identified articles, depicted in Fig. 2, were all 80 papers obtained from the second manual filtering. We adapted the concept matrix used by Webster and Watson (2002), who illustrates it as a logical approach that defines several *concepts* (e.g., variables, theories, topics, or methods) that serve as a classification scheme for grouping all relevant articles. Based on existing literature, we developed an initial concept matrix and added new concepts to it during the classification process.

Traditionally, the systematic literature review process is often done directly on a spreadsheet, including the list of identified articles and theoretical concepts for analysis. While this method was also considered for this study, we wanted to avoid handling a large matrix when conducting the coding with several authors at the same time, thus increasing the risk of making errors. Admittedly, working directly on the spreadsheet has some advantages as well; for example, it would have been easier to make changes when new concepts were introduced during the coding process.

However, at the same time, working with a spreadsheet can be overwhelming—in our case, 134 concepts were extracted from the literature. Consequently, as an alternative, we used an online questionnaire that was designed in a way that was consistent with the concept matrix we developed. Each page of the online questionnaire consisted of one analysis framework with corresponding concepts. The questionnaire form also enabled us to include the definitions and explanations of each concept, which was helpful to ensure a unified coding process. We further added an open text field for each framework. In this manner, the coders could propose new concepts or add notes about their coding decisions. In summary, the method ensured more consistent coding results and made it easier to work simultaneously during the coding process. Eventually, the results were stored in a single spreadsheet for analysis. For consolidating the results, we used the classification frameworks as described in Section 4.5.2 to 4.5.5.

4.5.2. Research design framework

We used existing research design categories without proposing new ones. Different authors have different ways of categorizing research designs, depending on the research perspective being used. Kumar (2019), for instance, divides research based on the study results' applications, the objective of the study, and the mode of enquiry used. According to Kumar (2019), research can either be pure or applied from an application perspective and can be descriptive, exploratory, correlational, or explanatory from a research objective perspective. From the mode of enquiry perspective, research can either be structured or unstructured. Creswell and Creswell (2017) divides research designs into qualitative, quantitative, and mixed methods, while Spector and Spector (1981) distinguishes between experimental and non-experimental research designs. In this study, we adapted the work of Wendler (2012), who classifies research design into the following categories: empirical qualitative research, empirical quantitative research, conceptual research, and design-oriented research. The definition of each category is given in Table 4.

4.5.3. Data collection methods and data analysis framework

We combined existing, established data collection methods both in qualitative and quantitative studies with our findings during the review process. The categories are compiled in Table 5.

The data analysis framework emerged through the coding process, as we extracted only the methods that were explicitly mentioned by authors. We further added the category of descriptive statistics, which was chosen when authors of the papers from our search presented their results by reporting frequencies, percentages, means, and standard deviations. The following data analysis methods were mentioned by the authors: descriptive statistics, t-test, correlation, analysis of variance (ANOVA), chi-square test, Fisher's exact test, Mann–Whitney U test, Mc Nemar's Test, multilevel linear modeling, qualitative analysis technique, and analysis of co-variance (ANCOVA). If the study did not have recognizable data analysis at all, then "No Method Applied" was chosen.

Table 5
Data collection methods.

Categories	Explanation
Development	A design- or development-oriented study that documents the overall development process.
Experimental design, usability, user testing	A study that is designed as an experimental study—e.g., a study that compares the performance of two groups or a study that includes usability or user testing.
Survey	A study that collects data from questionnaires, either paper-based or in the form of an online survey.
Interview, focus group discussion	A study that collects or explores the attitudes, opinions, or perceptions toward an issue, a service, a technology, or an application that allows for an open discussion between members of a group. Studies that collect opinions from individual subjects are also included here.
Observation	A study that collects and records information descriptively by observing the behaviors or social interactions of a subject or a group, either in an obtrusive or non-obtrusive way.
Case study, action research	A study that intends to improve and advance practice and is conducted in an iterative way, through identifying areas of concern, developing and testing alternatives, and experimenting with a new approach. This category also includes case studies in which the information is collected from a bounded system, a population, or a specific entity.
Literature Review	A study that collects information from existing literature and uses a systematic method to synthesize the results.
Mobile sensing	A study that collects information from mobile sensors.
Interaction log in VR app	A study that collects information from a developed VR app (e.g., user activities) and uses the resulting interaction log for analysis.
No method applied	A study that does not have a recognizable data collection method at all.

Table 6
Learning theory framework.

Categories	Explanation
Behavioral learning	When students receive either rewards or punishments for correct or incorrect answers and can thus learn the consequences of certain behavior (Shuell, 1986; Skinner, 1989). This applies to VR applications that include a system that allows the students to learn—e.g., responses resulting in satisfying (rewarding) consequences or responses producing annoying (punishing) consequences or learning what the consequences are for following or not following the rules. The students learn when their responses produce certain outcomes and allow them to adapt to their environments.
Experiential learning	When students learn through hands-on experience and using analytical skills to reflect on their experience (Kolb & Kolb, 2012). These reflections lead to changes in judgment, feelings, or skills of the student.
Generative learning	When students engage in cognitive processing during learning, including selecting (i.e., paying attention to relevant incoming information), organizing (i.e., mentally arranging the information into a coherent structure), and integrating (i.e., connecting the verbal and pictorial representations with one another and with relevant prior knowledge activated from long-term memory) (Parong & Mayer, 2018).
Operational learning	When students learn how to construct or assemble an object—as they do in Zhou, Ji, Xu, and Wang (2018)), where the students can interact, select, grasp, move, point, and place objects to learn computer assembly.
Game-based learning	When students learn through a gamification process, i.e., the use of game design elements and mechanics—such as points, levels, and badges—and game dynamics—such as rewards, statuses, and competition—in the learning process. An example of this is found in the work of Bryan, Campbell, and Mangina (2018), where the authors include gamification in the VR application, allowing the students to travel to different countries around the world, explore these locations, learn facts, and answer questions.
Contextual learning	When students learn by emphasizing the context, i.e., the set of circumstances that are relevant for the learners to build their knowledge. Hence, the learning content can assist in guiding students toward developing insights through balanced, organic, and successful environments and strategies. An example of this is a setting in which students use VR that encourages a more complex and higher level of thinking in order to improve their phonological, morphological, grammar, and syntax knowledge, as applied by Chen (2016).
Jeffries simulation theory	When students learn through a simulation process and experience in a trusted environment that is incorporated in the VR design (Jeffries, Rodgers, & Adamson, 2015).
Cone of learning theory	When students learn through both active and passive learning that involves direct, purposeful learning experiences, such as hands-on or field experience. According to this theory, students learn best when they go through a real experience or that experience is simulated in a realistic way. This theory is also known as Dale's Cone theory (Dale, 1969).

4.5.4. Learning framework: Learning theory and learning content

Similar to the data analysis framework, the learning theory framework emerged through the coding process and we only extracted those learning theories that were explicitly mentioned by authors. Details are given in Table 6. In contrast, Table 7 was first populated with initial concepts but, then, new categories were gradually established and incorporated into the framework during the coding process. The first four types of learning content emerged from the literature (cf. with the works of Anderson (1982) and Crebert, Bates, Bell, Patrick, and Cragnolini (2004)).

Table 7
Learning content framework.

Categories	Explanation
Analytical and problem-solving	Whether the use of VR can encourage students to improve their analytical skills, such as collecting and analyzing data, writing computer programs, or making complex decisions.
Communication, collaboration, soft skills	Whether the use of VR is intended to strengthen the students' ability to work in a team or whether students can improve their communication skills (e.g., presenting in front of an audience). This category also includes soft skills, such as management and leadership competencies.
Procedural–practical knowledge	Where the use of VR aims to assist students with internalizing procedures, such as knowing how to perform a surgery or how to perform firefighting procedures.
Declarative knowledge	Where the use of VR is intended to help students memorize factual knowledge (e.g., theoretical concepts and scientific principles). This includes, for example, learning the names of planets in our solar system.
Learning a language	Where the use of VR aims to improve students' foreign language capabilities, such as reading, listening, writing, and speaking.
Behavioral impacts	Where the use of VR aims to change the behavior of students by, for example, improving their learning habits, awareness of mobbing, and compliance to rules.
Others	Articles that could not be classified into the alternative concepts above.
Not specified	Where there is no statement or implicit information about the expected learning outcome of VR usage.

4.5.5. Design element framework

As in the learning framework, the design elements of VR for education also emerged from articles during the review process. Some of the categories had previously been proposed by Wohlgenannt, Fromm, Stieglitz, Radianti, and Majchrzak (2019) but our work, as listed in Table 8, provides an extensive update.

5. Results and analysis

In the following section, the results of the systematic mapping study are described according to the research questions (see Table 2, p. 9). Of the 38 articles included in our analysis, 68% originated from conferences, whereas 32% were published in journals (cf. Fig. 3). Our search window was 2016–2018. However, we also included one paper that was issued in 2015 because the acceptance for the online publication of this paper was 2015 but the actual journal publication date was in 2016. The number of journal publications in 2018 was remarkable, indicating an increasing scholarly interest in VR for higher education.

5.1. VR technologies (RQ1: What types of immersive VR technologies are used in higher education?)

As illustrated in Fig. 4, our review shows that 76% of the studies used high-end HMDs, such as Oculus Rift or HTC Vive. Many of these high-end VR systems use various supporting tools, such as controllers, touchpads, and haptic feedback. Out of 41 VR technology counts, eight used low-budget mobile VR, for instance, Ye, Hu, Zhou, Lei, and Guan (2018) used a smartphone and Google Cardboard for the VR environment. However, interactive manipulation was performed through a desktop monitor connected to the mobile app.

Only a few of the articles used enhanced VR, for instance, dela Cruz and Mendoza (2018), Veronez, Gonzaga, Bordin, Kupssinsku, Kannenberg, Duarte, et al. (2018), and Pena and Ragan (2017). For example, Veronez et al. (2018) used an additional G27 Racing Wheel to control the VR environment. 2% of the articles did not specifically mention the VR technology employed. It should also be noted that, in some experiments, two technologies were used, as in Bujdosó, Novac, and Szimkovics (2017), Webster and Dues (2017) and Buń, Trojanowska, Ivanov, and Pavlenko (2018), leading to a higher count than that of the number of papers. Overall, high-end HMDs were the most commonly used immersive VR technology.

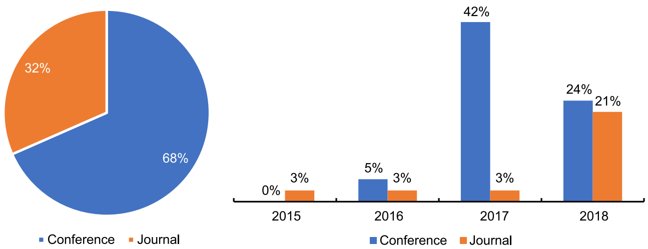

Fig. 3. Publication outlets and publication years of the 38 selected papers.

Table 8
Design element definition.

Categories	Explanation
Realistic surroundings	The virtual environment is of high graphic quality and has been designed to replicate a specific environment in the real world. For example, this applies to medical students who develop their surgery skills in an authentic-looking operation room.
Passive observation	Students can look around the virtual environment. This design element also applies to applications in which users can travel along a predefined path and look around while doing so. However, they are neither able to move around on their own nor to interact with virtual objects or other users.
Moving around	Students can explore the virtual environment on their own by teleporting or flying around.
Basic interaction with objects	Students can select virtual objects and interact with them in different ways. This includes retrieving additional information about an object in written or spoken form, taking and rotating it, zooming in on objects to see more details, and changing an object's color or shape.
Assembling objects	Students can select virtual objects and put them together, including the creation of new objects by assembling several individual objects.
Interaction with other users	Students can interact with other students or teachers. The interaction can take place in form of an avatar and via communication tools such as instant messaging or voice chat. This design element also includes the possibility of students visiting each other's virtual learning spaces.
Role management	The VR application offers different functionalities for different roles. A distinction is made between the role of a student and the role of a teacher. For a teacher, the VR application offers extended functionalities, such as assigning and evaluating learning tasks or viewing the learning progress of students.
Screen sharing	The VR application allows students and teachers to stream applications and files from their local desktop onto virtual screens. This allows them to share and edit content from their local desktops with other users in the virtual environment (e.g., PowerPoint, Google Drive, and Google Docs).
User-generated content	Students can create new content, such as 3D models, and upload this new content to the virtual environment. This design element also applies when the user-generated content can be shared with other users so that they can use it in their virtual environment as well. This design element does not apply when students can only access virtual objects that were created by developers and provided by a library in the virtual environment.
Instructions	Students have access to a tutorial or to instructions on how to use the VR application and how to perform the learning tasks. The instructions can be given by text, audio, or a virtual agent. This design element does not apply when students have to discover how to use the virtual environment or how to perform learning tasks on their own.
Immediate feedback	Students receive immediate textual, auditory, or haptic feedback. The feedback informs students about whether they have solved the learning tasks correctly and whether interactions with virtual objects were successful. In some cases, feedback may also be provided by simulating the results of an interaction with virtual objects, for example, when the corresponding chemical reaction is simulated after chemicals have been mixed in a virtual laboratory.
Knowledge test	Students can check their learning progress through knowledge tests, quizzes, or challenges.
Virtual rewards	Students can receive virtual rewards for successfully completing learning tasks. Students can be rewarded virtually by receiving achievements, badges, higher ranks on a leader board, and by unlocking exclusive content, such as hidden rooms or additional learning content.
Making meaningful choices	Students learn in the virtual environment through participating in a scenario (role-playing) that can end in different ways. In this scenario, they have to make decisions that affect the outcome of the scenario. This design element does not apply when the students' decisions have no influence on the outcome of the scenario.

5.2. Research designs (RQ2: Which research designs, data collection methods, and data analysis methods are applied to examine the use of immersive VR in higher education?)

Concerning the research method, *development* research was popular in 26 articles, as seen in the upper-left bar chart of Fig. 5, followed by experimental design, usability, and user testing (18 articles) as well as survey (16 articles). The bar chart in the upper-right of Fig. 5 shows the data analysis method. Both qualitative and quantitative data analysis methods were applied. The t-test (16) was the most commonly applied quantitative data analysis method. Conversely, other methods were rarely used, in only one to three articles on average, except for the correlation method (5 articles). However, it was a bit counterintuitive that most papers had no explicit or recognizable data analysis method (18 articles). Only four papers used qualitative data analysis methods, which included observations and focus group discussions.

We looked deeper into the relationship between the research design, research method, and data analysis method, as presented in two bubble charts in the lower part of Fig. 5. It should be noted here that the number of articles in the bubble charts adds up to a higher number than shown in the bar charts because one article may contain more than one category of research design. The research design categories in the middle can be read in combination with the bubble charts on the left and the right sides. The bubble charts depict the concentration of the studies. The combination of the data collection method and the research design is shown in the bottom left bubble chart of Fig. 5.

It shows that design-oriented, empirical quantitative, and empirical qualitative research were the dominant research contents. Most of the design-oriented works had combined their studies with development (24 articles), experimental design, usability, and user testing (11 articles), or had used interviews and focus group discussions to collect data (11 articles). This pattern is similar to other empirical qualitative and empirical quantitative studies. We discovered very few studies that were designed as conceptual

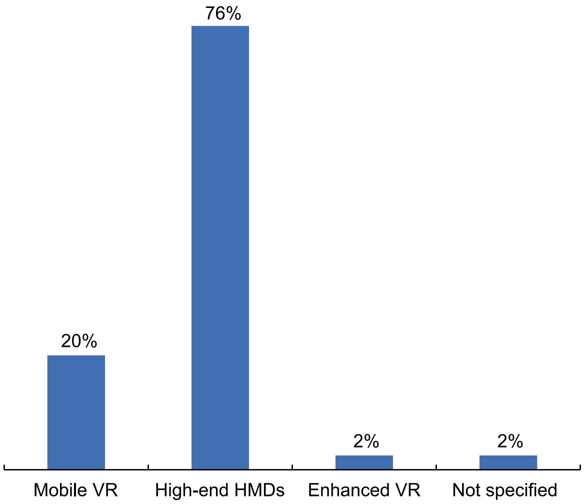

Fig. 4. VR technologies being used (n=41).

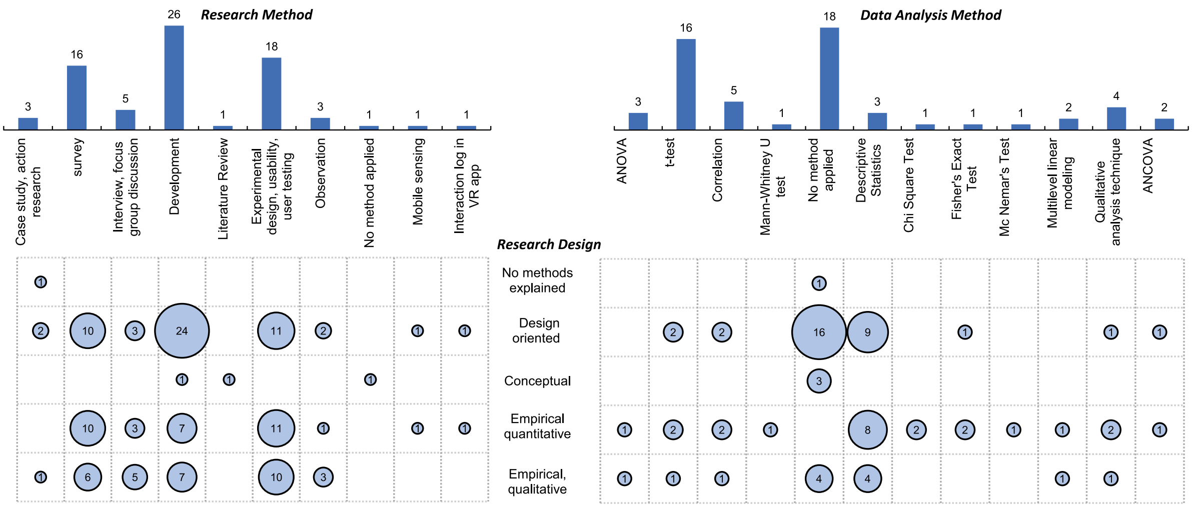

Fig. 5. Research design, data collection method, and data analysis method.

and these used a development approach (Chin et al., 2017), a literature review (Ekkelenkamp, Koch, de Man, & Kuipers, 2016), or did not mention any data collection method.

The bubble chart on the opposite side shows the combination of research design and data analysis method. Interestingly, most studies that reported no data analysis methods were design-oriented (16 articles). The majority of studies that employed a design-oriented research approach primarily reported only descriptive statistics (9 articles). Apart from this, empirical quantitative research designs employed a wide range of identified data analysis methods, with less visible concentrations. In addition, several of the empirical qualitative studies reported descriptive statistics as well (4 articles). Furthermore, we identified that this category had also employed ANOVA, t-test, correlation, multilevel linear modeling, and other quantitative data analysis methods. Four articles mentioned no explicit data analysis method. Likewise, of the conceptual research design articles, three had not applied any method.

5.3. Learning theories (RQ3: What learning theories are applied to examine the use of immersive VR in higher education?)

Fig. 6 indicates that the literature which claims to create VR content or design VR applications for higher education surprisingly lacked reference to explicit learning theories. Thus, the "not mentioned" category consists of 68% of all articles. It should also be noted that, during the coding, we avoided "reading between the lines" and only extracted the learning theories that were explicitly mentioned by study authors as their theoretical foundation. Among the articles that had a theoretical foundation, experiential learning accounts for 11% of all articles, while each of the remaining theories accounts for 3%. The other category consists of an article that explicitly mentions different learning theories, such as the constructivism learning theory, flow theory, gamification

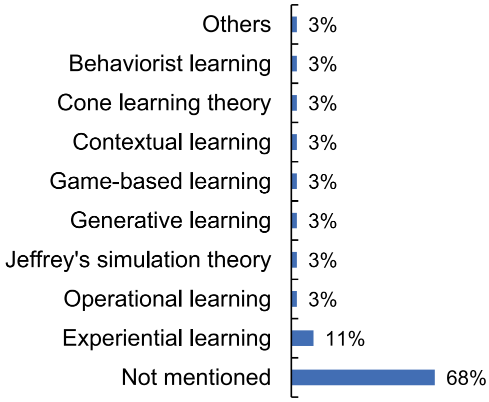

Fig. 6. Applied learning theories (n=38).

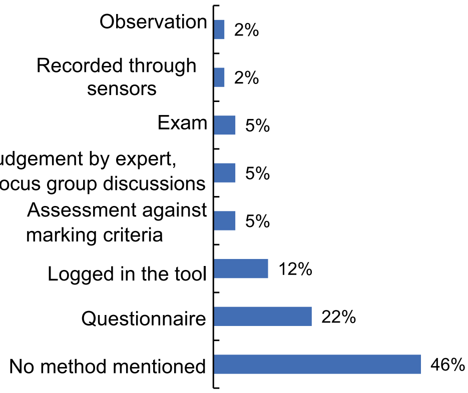

Fig. 7. Evaluation methods.

learning, transfer of learning in the literature review section, but its authors did not really claim which learning theory they prefer to use (e.g. Chen, 2016). The cone of learning theory was kept as a separate category, given the fact that authors explicitly used this theory in all development VR processes. Recent literature has grouped the cone of learning theory with that of experiential learning, (e.g., (Garrett, 1997)). However, many recent authors are still using this theory on its own (Davis & Summers, 2015) and, therefore, we placed it in a separate category.

5.4. Learning outcome evaluation (RQ4: Which research methods and techniques are applied to evaluate the learning outcomes of immersive VR usage in higher education?)

Almost half of the reviewed articles did not specify a learning outcome evaluation method (see Fig. 7). A few articles used questionnaires (22%) or user activities while logged into the VR application (12%). Exams, expert judgments, or focus group discussions accounted for a mere 5%, respectively, while the remaining articles used observations or sensor data. This fact is intriguing because many articles described evaluations of developed VR applications, however, the focus was mainly placed on usability or user experience. Nevertheless, there were also several articles that actually measured or evaluated how much the students' knowledge or skills progressed after the use of immersive VR, for example, Farra, Smith, and Ulrich (2018) and Zhang, Suo, Chen, Liu, and Gao (2017).

5.5. Application domain (RQ5: In what higher education application domains are immersive VR applications used?)

Engineering was the most popular application area identified in 24% of the articles (see Fig. 8). The next most popular application domains were computer science (10%) and astronomy (7%). The total number adds up to more than 38 articles because we found several articles that fell into more than one category. Furthermore, some articles were very generic and did not mention a specific domain (12%). This applied to the works by Hu, Su, and He (2016), Webster and Dues (2017), Yang, Cheng, and Yang (2016), Zizza et al. (2019), and Misbhauddin (2018).

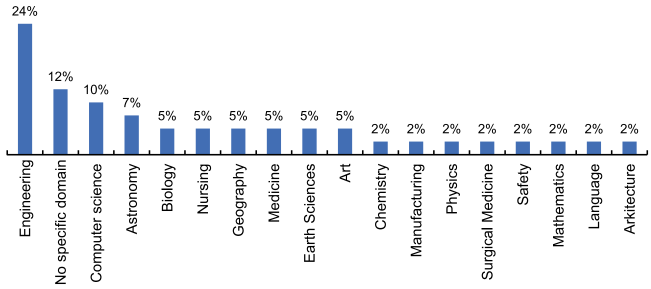

Fig. 8. Application domain (n=42).

Fig. 9. Learning content.

5.6. Learning content (RQ6: For which learning contents in higher education are immersive VR applications used?)

Fig. 9 shows that VR applications for higher education were most frequently used to teach: procedural–practical knowledge (33%), such as filing a report (Pena & Ragan, 2017) or extinguishing fires (Zhang et al., 2017); declarative knowledge (25%), such as learning planet names (Papachristos, Vrellis, & Mikropoulos, 2017) or theoretical concepts in pneumatics (dela Cruz & Mendoza, 2018); and analytical and problem-solving skills (12%), such as diagnosing patients (Harrington et al., 2018) or learning how to code (Román-Ibáñez, Pujol-López, Mora-Mora, Pertegal-Felices, & Jimeno-Morenilla, 2018). The rest of the learning content categories found in the literature were communication, collaboration, and soft skills (10%), behavioral impact (6%), and learning a language (2%). The categories others and not specified accounted for 6% and 4%.

5.7. Design elements (RQ7: What design elements are included in immersive VR applications for higher education?)

Basic interaction and realistic surroundings were the most frequently used design elements, accounting for 24% and 17% of the articles, respectively (see Fig. 10). Immediate feedback and instructions share an equal percentage, i.e., 10%. The next popular element is interaction with other users, which accounted for 9% of all category counts. Passive observation and assembly also shared an equal percentage of representation at 8% each. The rest of the design elements were included in 1%–4% of all papers, i.e., moving around (4%), user-generated content (3%), virtual rewards (2%), role management (2%), and knowledge test (2%). Both screen sharing and making meaningful choices accounted for 1% of all papers.

5.8. Mapping 1 (RQ8: What is the relationship between application domains and learning contents of immersive VR applications for higher education?)

The bubble chart in Fig. 11 links learning contents and application domains. The magnitude of the bubble corresponds to the number of articles found for a given combination. The number of articles was too small to generate clusters and such clustering would also be limited by the fact that application domains are not necessarily independent. Nevertheless, the mapping allowed for observations, although we could not generalize the relationships between the learning content and the application domain because

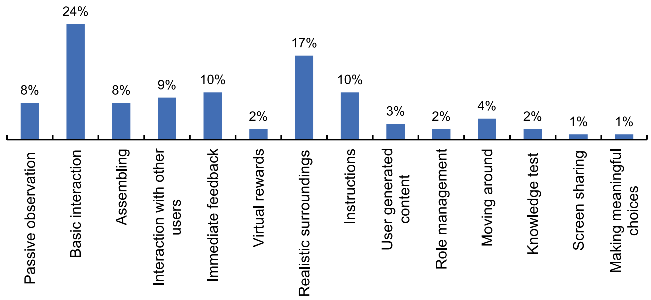

Fig. 10. Identified design elements.

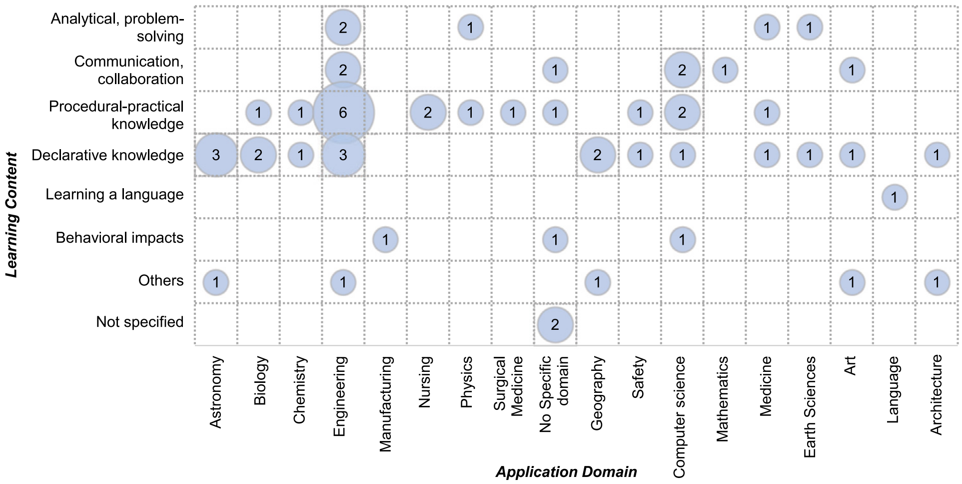

Fig. 11. Relationship between learning content and application domain.

too few relevant papers would be included. At the same time, learning contents were spread among application domains, indicating a wide variety of learning contents across disciplines.

The matrix in Fig. 11 is relatively sparse. While this, undoubtedly, can partly be explained by our attempt at making clear distinctions, it also hints at the experimental nature of the field. Moreover, we observed that no reasonable grouping of application domains – for example, biology, chemistry, and physics as natural sciences – would yield additional insights.

From the mapping, we observed that astronomy used either declarative knowledge (Němec, Fasuga, Trubač, & Kratochvíl, 2017; Rosenfield et al., 2018; Veronez et al., 2018) or "others", which included learning content for visualization and motivation. Both biology and chemistry paid attention to declarative knowledge and procedural or practical knowledge (e.g., the articles by AlAwadhi et al. (2017), Parong and Mayer (2018)). Since engineering is an application domain frequently described in the literature, it allowed for a diverse assessment. Engineering used the following learning contents: analytical and problem solving (Harrington et al., 2018; Parong & Mayer, 2018), communication and collaboration or soft skills (Hickman & Akdere, 2018; Ye et al., 2018), procedural and practical knowledge (AlAwadhi et al., 2017; Buń et al., 2018; dela Cruz & Mendoza, 2018; Román-Ibáñez et al., 2018; Schroeder, Bailey, Johnson, & Gonzalez-Holland, 2017), and declarative knowledge (AlAwadhi et al., 2017; Němec et al., 2017; Ye et al., 2018). The only manufacturing article we identified described behavioral impacts (Carruth, 2017).

Nursing (Farra et al., 2018; Smith et al., 2018), physics (Pirker, Lesjak, & Guetl, 2017), and surgical medicine (Ekkelenkamp et al., 2016) mainly focused on procedural knowledge. The articles on geography proposed an application to improve declarative knowledge (Bryan et al., 2018; Parong & Mayer, 2018). Similarly, for safety (Zhang et al., 2017), surgical medicine (Harrington et al., 2018), earth science (Chin et al., 2017; Gerloni et al., 2018), and architecture (Němec et al., 2017), articles describing declarative knowledge as the learning content could be identified, among diverse other aims. Not surprisingly, the only article we identified in the domain of language focused on teaching the skill of language learning (Chen, 2016).

Diverse pictures can be drawn for computer science and art. Art papers (Cortiz & Silva, 2017; Song & Li, 2018) varied in terms of learning content, as did the computer science articles. However, they emphased collaboration and communication (Bujdosó et al., 2017; Hickman & Akdere, 2018) as well as procedural and practical knowledge (Parmar, Isaac, Babu, D'Souza, Leonard, Jörg, Gundersen, & Daily, 2016; Zhou et al., 2018).

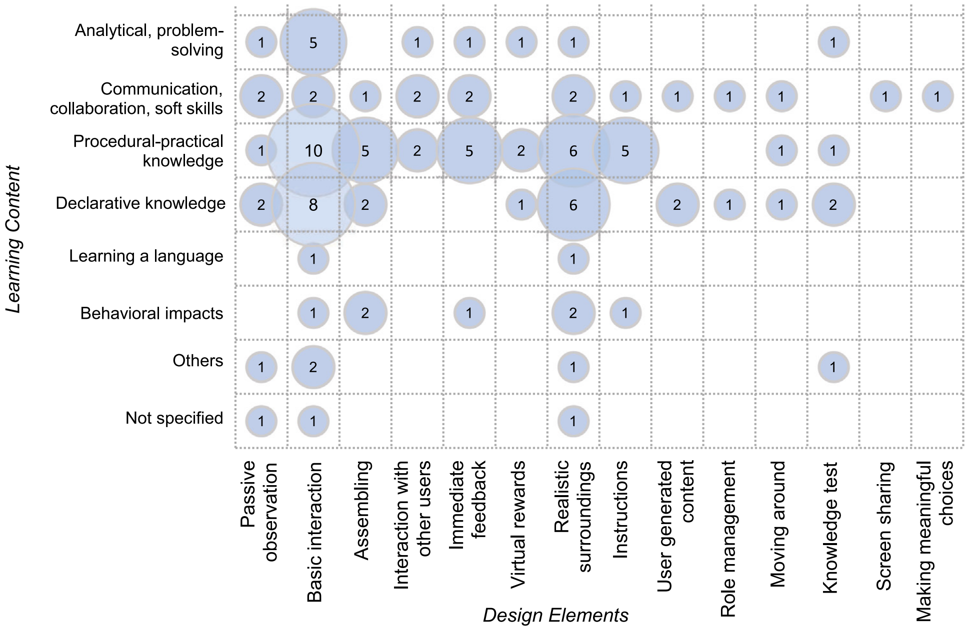

Fig. 12. Relationship between learning content and design elements.

5.9. Mapping 2 (RQ9: What is the relationship between learning contents and design elements of immersive VR applications for higher education?)

Fig. 12 illustrates the overall mapping results of design elements and learning contents. In this way, we analyzed whether there were patterns of certain design elements that were used in VR applications intended to teach specific learning contents. From Fig. 12, we can conclude that basic interaction and realistic surroundings were used for each type of learning content. These tendencies can be observed in the distribution of the bubbles spreading across all learning content categories. However, this observation is reasonable because most VR applications would need to have at least basic interaction elements and to be realistic enough to increase the immersive experience of users.

From the design element perspective, the basic interaction element was mostly applied in the procedural or practical knowledge-oriented VR applications (10 articles) (AlAwadhi et al., 2017; Buń et al., 2018; dela Cruz & Mendoza, 2018; Farra et al., 2018; Harrington et al., 2018; Ibanez, Kloos, Leony, Rueda, & Maroto, 2011; Pena & Ragan, 2017; Pirker et al., 2017; Smith et al., 2018; Zhang et al., 2017) and in the declarative knowledge-oriented VR applications (8 articles) (AlAwadhi et al., 2017; Bryan et al., 2018; Dolezal, Chmelik, & Liarokapis, 2017; Hu et al., 2016; Im, An, Kwon, & Kim, 2017; Němec et al., 2017; Rosenfield et al., 2018; Zhang et al., 2017). Likewise, the realistic-surroundings element was adopted for teaching procedural or practical knowledge and declarative knowledge contents. There were six articles in the former category (AlAwadhi et al., 2017; Buń et al., 2018; Ekkelenkamp et al., 2016; Im et al., 2017; Smith et al., 2018; Zhang et al., 2017) and six articles the latter category (AlAwadhi et al., 2017; Chin et al., 2017; Němec et al., 2017; Rosenfield et al., 2018; Ye et al., 2018; Zhang et al., 2017).

Furthermore, from the learning content perspective, seven or more design elements were applied by VR applications intending to teach the following learning contents: communication, collaboration, and soft skills (11 elements), procedural or practical knowledge (10 elements), declarative knowledge (9 elements), and analytical and problem solving skills (7 elements). The remaining categories used four or fewer design elements. On average, an article addressed one to five design elements. Hence, the total number of design elements per category could be higher than the number of articles. For instance, basic interaction and immediate feedback elements were identified in the study of Román-Ibáñez et al. (2018). Six design elements were recognized in the article by Dolezal et al. (2017)—basic interaction, interaction with users, immediate feedback, instructions, role management, and moving around. Zhang et al. (2017) adopted five design elements—basic interaction, immediate feedback, virtual rewards, realistic surrounding, and knowledge test. The majority of the articles in each category described more than two design elements.

Only a few articles used the following design elements: user-generated content, role management, moving around, knowledge test, screen sharing, and making a meaningful choice; these are mostly found in articles that contain multiple design elements.

There is no single rule about what design elements are valid for specific learning contents. Basic interaction, in particular, was found in all, regardless of the learning contents being addressed. AlAwadhi et al. (2017), Rosenfield et al. (2018), Zhang et al. (2017), and Němec et al. (2017) are examples of articles that aimed for declarative knowledge. Rosenfield et al. (2018) proposed the Worldwide Telescope 3D application for exploring the planetary surface, elevation maps, orbital path, ephemerides, and solar systems in a realistic manner. Zhang et al. (2017) built a VR environment for learning related to fire safety – fire type, fire hazard, fire alarm – and for providing knowledge about various safety evacuation signs in a virtual campus. AlAwadhi et al. (2017) suggested a VR design in order to conduct experiments, watch pre-recorded lectures, perform a campus tour, and recognize the components of informative labs. Both papers also contained practical–procedural content, i.e., how to conduct experiments (AlAwadhi et al., 2017) and how to prevent fire (Zhang et al., 2017). Němec et al. (2017) presented multiple realistic VR environment objects, such as human skeletons, solar system planets, architecture, machinery rooms, and power plants.

The articles by Smith et al. (2018) and Buń et al. (2018) are examples of studies that aimed at practical–procedural knowledge, containing both basic interaction and realistic surrounding design elements. Buń et al. (2018) used VR for improving the users' procedural knowledge regarding assembly operation in a manufacturing activity. The basic interactions could be recognized in the possibilities given to users to manipulate objects in a realistic manufacturing environment. Smith et al. (2018) applied VR to teach decontamination skills—e.g., how to pick up a patient's freshly cut off, contaminated clothing, and place them in a nearby biohazard bin. It was tailored with a realistic emergency room environment (Smith et al., 2018).

There were several design elements found in the analytical- and problem solving-oriented literature. Román-Ibáñez et al. (2018) described learning about robotic arm trajectories and collision detection with immediate feedback. Pena and Ragan (2017) suggested improving the analytical skill of recognizing accidents in an industrial setting by allowing users to move around in a virtual environment. Harrington et al. (2018) exploited gesture detection to increase the analytical skills used for decision-making when working with critically injured patients. Gerloni et al. (2018) proposed the ARGO3D platform for learning about geological information and geohazards, such as the crater of an active volcano, in a realistic environment. The platform allows students to navigate inside the environment, fly around, and take pictures. Veronez et al. (2018) developed a VR system to teach the analytical skills necessary for assessing road safety, while Pirker et al. (2017) provided an example of how VR could improve analytical skills through experimentation in a virtual physics lab.

To improve communication, collaboration, and soft skills, several design elements were implemented in the literature. Bujdosó et al. (2017) suggested MaxWhere as a VR collaborative arena (ViRCA) for encouraging interactions with other students. In this example, it is possible to assign tasks to others, generate new content, and work in shared documents. Zizza et al. (2019) suggested the VRLE platform, involving one instructor and a group of students, to improve social competencies and social interaction. The users interact with the environment, as well as with instructors and peers, using virtual hands and voices. Ye et al. (2018) used assembling elements as part of a soft skill to comprehend the control parameters in the automatic control system and to detect abnormalities of the system.

Cortiz and Silva (2017) used passive observation to learn art history through VR in which students can add more content into the learning material, such as artwork from a well-known artist. Hickman and Akdere (2018) reported a conceptual work that describes a possible VR platform for improving intercultural leadership, which included design elements such as passive observation, immediate feedback, and realistic surroundings.

There were 17 papers identified for improving procedural and practical knowledge. For example, Muller, Panzoli, Galaup, Lagarrigue, and Jessel (2017) adopted assembling as the main design element to teach the procedure of setting up a tailstock, palping, and operating machine. An information and instruction set appears in the VR menu as part of its design elements. Im et al. (2017) used VR for technical training. Misbhauddin (2018) suggested VREdu for providing an immersive lecture, where the platform incorporates role management elements that allow different access for students and instructors. It was streamed to users using the chunking method, i.e., a segment of the video was saved, uploaded to the server, and broadcast.

There were 13 papers that sought to improve declarative knowledge. Dolezal et al. (2017) developed a collaborative virtual environment for geovisualization, where a virtual world is shared by users with avatars through a computer network. This virtual environment supports role management by providing different user rights to teachers and students. The tutorial was important in this work, as part of the instruction design element. The immediate feedback element could be recognized in the possibility provided to the teacher to press a button and reveal the correct and incorrect answers. Zhang et al. (2017) developed fire safety VR with mostly basic interaction elements. Bryan et al. (2018) introduced Scenic Spheres, which allows students to travel around the world, learn facts, and get a feeling about local culture.

Only a few articles focused on learning a language, pedagogical impacts, behavioral impacts, other areas (not falling into an existing category), and areas not specified (having no recognizable learning content). Typically, such works had multiple design elements. Only one paper proposed learning language content (Chen, 2016) and used the realistic surroundings element that captures a situation to be used to learn morphology, phonology, grammar, and syntax. It also used some basic interaction elements in VR such as selecting an object.

The articles aiming to change perceptions, attitude, and actions toward certain issues were categorized as having behavioral impacts learning content. Parmar et al. (2016) introduced Virtual Environment Interaction (VEnvI) for teaching programming, logic, and computational thinking in combination with dancing. Users can select dance movements and generate pseudo-code as visual programming. Additionally, they can select drag and drop options for different movements or steps, such as moving forward, backward, squatting, and jumping, and can also simultaneously see a co-located virtual self-avatar that mimics their own movements, look around in the virtual world, and experience a high degree of presence. The behavioral impact happened is found in terms of changing perception toward computer science and computer scientists by highlighting that learning programming could be fun.

Hu et al. (2016) used VR for safety education and environmental protection. The users can collect and classify virtual objects as a basic interaction element and can receive rewards when they perform correctly as a feedback mechanism. The behavioral impact here is with respect to improving actions toward environmental protection. Carruth (2017) developed two VR showcases for industrial applications, such as familiarizing oneself with industrial workspaces, tools, and safety, in a realistic VR environment. Users can interact with this VR environment by picking up tools, manipulating them, and exploring a full range of physical interactions that represent the assembling element. The behavior changes in this work regard improved awareness of industrial safety and increased knowledge on the usage of tools in an industrial setting.

The visualization-oriented content (Němec et al., 2017) and motivation content papers (Song & Li, 2018) were merged into the "others" category. In addition, a few of the papers did not easily allow us to derive any design elements and learning content (Webster & Dues, 2017; Yang et al., 2016). Hence, these were classified as papers with "no specific elements".

In a final remark to RQ9, we can summarize the common design elements found in the literature, such as basic interaction and immediate feedback. Typical basic interactions found in the literature were achieved through two levels: first, through user interactions with the VR hardware (e.g., controllers) and, second, through the user interactions inside the VR environment.

Concerning the user interactions with the VR hardware, the following eight types of design were primarily found in the literature. First, head movement detection through sensors embedded in the headset was a basic interaction used to obtain an approximation of the head orientation (Román-Ibáñez et al., 2018) or the addition of a 360° camera (AlAwadhi et al., 2017). Second, motion and infrared sensors were used to transcribe head movements of pitch (up–down), yaw (side to side), and roll (rotational) in order to allow for orientation within the virtual space (Harrington et al., 2018) and track the user's position (Gerloni et al., 2018; Im et al., 2017). Third, pressing-down a touchpad on the controller or clicking on a map to teleport to the desired location (Pena & Ragan, 2017) was used in order to interact with objects, instruments, or text within the VR platform (Harrington et al., 2018). Fourth, handheld input with thumbsticks (Gerloni et al., 2018), hand-held controllers, and base-stations were used for accurate localization and tracking of the controllers (Zizza et al., 2019). Fifth, attaching a racing wheel system was used to enable realistic driving, such as changing gears manually (Veronez et al., 2018). Sixth, integrated realistic haptic of the VR controllers was sometimes accompanied by a dual-stage trigger with 24 sensors (Pirker et al., 2017; Zhang et al., 2017)—this can be used to track the natural behavior of users, such as moving forward and backward, squatting, grabbing, and releasing. Seventh, sensor technologies – such as galvanic skin response, and facial emotion detection – were used to detect emotions (Hickman & Akdere, 2018). Eighth, interacting through one button only was also used (Muller et al., 2017).

With respect to the interaction inside the VR environment, nine capabilities were revealed in the literature. First, the ability to manipulate objects in various ways—rotation, placement, or moving the objects using a natural virtual hand metaphor (Zizza et al., 2019). Second, the ability to grab objects, such as stickers that can be put on a map (Dolezal et al., 2017). Third, basic pause and repeat, customizable voice notes, and recall abilities (Im et al., 2017). Fourth, the ability to select menu, drag, drop, and look around using a built-in head tracking functionality (Bryan et al., 2018; Song & Li, 2018). Fifth, the ability to interact with language modules. Sixth, the ability to observe objects, such as numerous art exhibitions or artistic design works (Song & Li, 2018). Seventh, the ability to perform experiments, watch pre-recorded lectures, move around the campus, and touch objects (AlAwadhi et al., 2017). Eighth, the ability to collect and classify virtual objects (Hu et al., 2016), pick up tools, manipulate them, and explore a full range of physical interactions (Carruth, 2017). Ninth, the ability to look around in the environment (Bryan et al., 2018).

Typical immediate feedback often used in the literature was as follows: alert systems (Román-Ibáñez et al., 2018); sounds to signal an incorrect gear change (Veronez et al., 2018) or the success and failure when conducting technical works (Im et al., 2017); virtual hands and voices (Zizza et al., 2019); display of the data stream that updates the status of an object (Ye et al., 2018); provision of immediate feedback to students through controller vibration when selecting an object in a VR environment (Muller et al., 2017); revealing correct and incorrect answers by pressing a button (Dolezal et al., 2017); receiving scores after answering a quiz that appears in the VR environment (AlAwadhi et al., 2017) or when a user performs a correct action (Hu et al., 2016); and multisensory, visual feedback, such as highlights, signs, and haptic feedback, that allow users to "feel" the virtual objects (Carruth, 2017).

6. Discussion

In the following section, we discuss the results by describing implications, suggesting a research agenda, deriving recommendations, and identifying limitations.

6.1. Implications

The use of the term *immersion* in connection to VR technology usage has been understood differently. We had to exclude many papers during our evaluation process due to their incompatible use of this term, which was often applied to non-immersive technologies. We included a high number of inclusion terms related to immersive technologies, such as Oculus, Vive, Samsung Gear, Google Cardboard, and Samsung Odyssey, and excluded as many non-immersive technologies as possible, such as 360-degree videos, Desktop VR, CAVE, and panoramic videos. Unfortunately, there is still ambiguity and non-homogeneous understanding of the equipment that can be considered as "immersive technology".

Regarding *learning theories*, three common types of articles were found in the literature. First, those articles that described VR applications for higher education in detail often did not mention explicit learning theories as their theoretical foundation (68%). In these articles, the development of the VR applications was described thoroughly but the evaluation focused mainly on usability. Such described works, therefore, had an experimental character and were reproducible to some degree only, let alone generalizable. Second, the articles that described VR development in-depth and also mentioned learning theories were often disconnected. For instance, the authors only evaluated app features or usability but not the learning outcomes. Third, there were articles that highlighted the underlying theories of educational VR design but did not report on the technical development in detail. As a result, it was often hard to extract design elements from these papers.

In the 38 reviewed articles, we could identify 18 *application domains*, indicating that there is an interest in the use of immersive VR technologies in many different fields, especially in engineering and computer science. However, this impression must be treated cautiously because most articles did not report experiences with or lessons learned from implementing VR in real university courses. The majority reported on the development process or explored potential uses of VR-based learning.

In some areas, VR seemed to be *mature* enough to be used for teaching procedural, practical knowledge and declarative knowledge. Examples included fire safety, surgery, nursing, and astronomy. In these cases, more professional VR applications were used and were proven to be appropriate for learning in higher education. However, the majority of articles indicated that VR for education is still in its experimental stages—prototyping and testing with students.

Few papers *evaluated* the learning outcomes after applying VR in a specific domain and most of the evaluations that were made consisted of usability-oriented tests. This is also another indicator of the VR maturity level, which still remains a barrier for its adoption in regular teaching activities.

As the only *design element*, basic interactions apparently appear in all types of VR learning content. However, upon a closer look, authors highlight two different levels of user interactions: (1) interactions that occur inside the VR environment and (2) interactions with the hardware, such as the exploitation of haptic and sensors in the headset or other physical objects that connect users with the VR objects. Many papers claim to have created VR for specific purposes in a *realistic* environment and the element “realistic surrounding” was found in almost all learning contents. The terminology of realism is still not uniform, however, as some papers understood realistic surroundings to be a high-fidelity VR environment with complex, high-quality graphics, while for others it could also mean “realistic enough”, in that the user can recognize the environments or the objects, without the creation of objects with real-world details.

6.2. Research agenda and recommendations

Our literature analysis indicated that the interest in applying immersive VR for educational purposes has increased. At the same time, a very low maturity of the field needs to be ascertained. Based on the lessons learned, the following research agenda can be proposed.

First, the theory on VR for educational applications is apparently not advanced enough to allow for a homogeneous usage of related terms, such as immersion or realism. To mitigate the retarding effect of ambiguity and unclarity, more work is required that seeks to contribute toward a common understanding. On the basis of articles such as ours, which summarize categorization frameworks from theory and which seek to classify other works based on sound criteria, a common understanding can be built. Ultimately, proposing a taxonomy of learning theories and other framing factors for educational VR applications is a future research task.

Second, future VR development for higher education needs to built on existing experiments (rather than being exploratory from scratch) and to provide results that allow for generalization. There is no general issue with design-oriented or even mostly developmental works. However, to make thorough contributions, such works need to take a holistic standpoint. Our work clearly indicates that a high contribution and impact can be expected from articles that have a sound theoretical foundation (e.g., learning theories) and technological foundation (e.g., careful selection of design elements) but are also explicit in describing the design and development process. Admittedly, such interdisciplinary work can be hard to develop. Thus, providing the necessary theoretical background to build novel educational VR applications is a future research task. Several aspects of generalization will be supportive. Technology generalization is driven by work that is outside of the educational context but can make the design of such applications much easier. Generalization of learning methods and design elements would help to better the sharing of good practices and to design new course content more rapidly even outside of the fields in which VR has already worked well. As part of this future research task, researchers will also need a comprehensive market overview of existing VR applications that support education. Industrial applications might lead the way to theory building by scientists as well as to the creation of new applications in the educational context.

Third, such works will also allow for a better adoption of VR in higher education. There is currently little exchange of best practices related to education-oriented VR—either within or across disciplines. For example, VR applications in the natural sciences might be more similar to one another than, for example, VR applications in the arts. Thus, the research aim again needs to be holistic and to include well-evaluated works that intend to extend the body of knowledge rather than to simply report anecdotal findings. This will also help derive best practices from the few applications in which VR is already being used with very good learning outcomes.

Fourth, to fulfill the aim of deriving best practices and of describing useful application cases, better evaluation procedures are needed. It is typical that experimental works place the main focus on usability. However, future educational VR applications should be more thoroughly evaluated by employing quantitative and qualitative research methods to assess the students’ increase of knowledge and skills as well as the students’ learning experience. Evaluations of educational VR applications need to be conducted both in terms of technical feasibility (i.e., from a software engineering standpoint) and of the learning outcomes (i.e., from a pedagogical standpoint). We also suggest that future evaluations assess whether developed applications reflect the users’ needs, from the perspective of both teachers and students. Thus, future research needs to include workshops, surveys, and focus group discussions in order to extract the necessary learning content and the expected learning outcomes as well as the usability requirements for VR applications from teachers and students.

Fifth, technological progress is needed to create environments that are perceived as realistic, thus providing *real* immersion. This research aim is not bound to the realm of education. In fact, education can build on high-paced developments, e.g., with respect to gaming, which leads to better development frameworks and fosters the understanding of *how* to create immersion.

Sixth, the eventual aim might be an inclusion of VR into higher education curricula. Such an inclusion could be twofold: (1) VR could be utilized as a teaching tool in real university courses to improve learning outcomes and (2) VR could become the teaching subject itself. The latter would cater to VR becoming more important for application in more and more professional domains. For the inclusion of VR in curricula, much more work is needed on the role of the design elements and the design of learning contents for VR.

6.3. Recommendations for lecturers

Our research shows that the "realistic surroundings" and "basic interaction" design elements occur in all types of VR applications in our sample. Thus, these can be seen as the basic design requirements for educational VR applications. VR applications that aim to improve declarative knowledge can be recommended for initiating VR in the courses. In our mapping of design elements and learning outcomes, we can see that most applications for declarative knowledge use only these two basic design elements. Therefore, these elements can be a soft start for VR development, easy to use by lecturers and students, and might not require any changes in the curriculum. In many study programs, students are mainly taught declarative knowledge in lectures and are expected to memorize what they have learned for exams. The use of VR applications to impart declarative knowledge could support this learning method to make lectures more exciting.

From our own experience as lecturers, we recognize the students' wishes on practice-oriented learning contents rather than memorizing facts. If lecturers have already had good experiences with VR in their lectures, they could use advanced applications to make teaching more practice-oriented. In our sample, most articles describe VR applications for teaching procedural knowledge. At the same time, our mapping of design elements and learning outcomes shows that these applications have the largest number of design elements. This means that the development of such applications is more complex and that teachers and students might need more VR experience to apply them. Furthermore, it might require complex changes of the curriculum to shift the focus from teaching declarative knowledge to more practice-oriented content. Nevertheless, we believe that the true potential of VR lies not in better teaching of declarative knowledge, but in offering opportunities to "learn by doing" which is often very difficult to implement in traditional lectures.

We have limited results concerning VR aims at improving communication, collaboration and soft skills, behavioral impacts and analytical skills to be able to derive recommendations for the most useful design elements that will meet specific learning goals.

Revisiting our findings and the research agenda, we conclude that the state of the art does not allow for the provision of an exhaustive set of recommendations or even a catalogue of best practices. Nonetheless, it is possible to propose an initial list of ideas for teachers in higher education. It should help them decide when to use VR, for which purposes to use it, and which technological steps to take.

Undoubtedly, VR is a hyped topic that does not only tend to make technological enthusiasts excited. This momentum can be used by educators and chances are good for someone to be an early adopter and to make a contribution. Thus, our recommendation to interested educators is not to be too shy about applying VR to their curricula. They should also be empowered to become capable of deciding on buying apps, cooperating with the industry, and developing requirements—it does not seem realistic that non-technologists will be able to develop arbitrary virtual worlds from scratch in the near future.

Since VR applications exist in some fields, it makes much sense to learn from existing *good* cases. Even without a body of best practices, *solid cases* can be used as an indicator of what works. Solid in this sense could mean that a VR application in higher education is built with sound technology, is explicit about learning aims and design elements, and has been evaluated thoroughly. Thus, we recommend that such works are built on and that attempts are made to transfer positive experiences as far as possible to their own application domain.

There are many technological hurdles. The price tag of VR can be very high—maybe too high to be convincing, as long as a positive impact on learning is not proven. Thus, we recommend starting with a realistically small scope and tailoring the application case to what seems feasible and achievable in a timespan of a few months. Setting out to virtualize a whole course with all its assets is bound to fail even if plentiful resources (e.g., funding and VR-proficient personnel) are available. However, the integration of low-budget mobile HMDs or the use of VR applications in a few selected lecture units over the entire semester could represent first steps toward a broad adoption of VR in higher education.

6.4. Limitations

Due to the nature of the review, selection, and filtering process, our work has several limitations. First, we only looked at immersive VR applications for education. There are various VR technologies, other than HMDs, that have been used for educational purposes, such as 360-degree videos, desktop VR, and mixed reality. These technologies might already have achieved a higher level of maturity and have been successfully applied for higher education purposes. It is worth acknowledging that as the focus of this study has been on learning through HMDs VR engagement, the paper does not consider emerging applications and studies applying collaborative and group engagement in VR through VR domes/other multiple person VR environments (Grogorick, Ueberheide, Tauscher, Bittner, & Magnor, 2019; Liu, Liu, & Jin, 2019). Future work might need to seek drawing the *whole picture*.

Second, we also limited ourselves to publications appearing between 2016 and 2018, assuming this to be a timeline when HMDs gained popularity and may have changed the way VR is used in the education context. If the types of VR technologies used in education are not a limiting factor, there are some innovative VR-based teaching and learning approaches that have been

Table A.9
Search strings.

Database	Results	Keyword search and other applied filters
Scopus	574	(TITLE-ABS-KEY (“virtual reality”) OR TITLE-ABS-KEY (“VR”) AND TITLE-ABS-KEY (educat*) OR TITLE-ABS-KEY (teach*) OR TITLE-ABS-KEY (learn*) OR TITLE-ABS-KEY (train*) AND TITLE-ABS-KEY (university) OR TITLE-ABS-KEY (“higher education”) OR TITLE-ABS-KEY (college) AND NOT TITLE-ABS-KEY (“machine learning”) OR TITLE-ABS-KEY (“deep learning”) AND NOT TITLE-ABS-KEY (“artificial intelligence”) OR TITLE-ABS-KEY (“neural network”) AND NOT TITLE-ABS-KEY (rehabilitation) OR TITLE-ABS-KEY (therapy)) AND DOCTYPE (ar OR cp) AND PUBYEAR > 2016 AND PUBYEAR < 2018 AND (LIMIT-TO (LANGUAGE , “English”))
IEEEXplore Digital Library	1 656	(“Abstract”:“virtual reality” OR “Abstract”:“VR” AND “Abstract”:“educat*” OR“Abstract” OR “Abstract”:“teach” OR “Abstract”:“train” AND “Abstract”:“university” OR “Abstract”:“higher education” OR “Abstract”:“college” NOT “Abstract”:“artificial intelligence” OR “Abstract”:“neural network” NOT “Abstract”:“rehabilitation” NOT “Abstract”:“machine learning” OR “Abstract”:“deep learning”). Filters Applied: Journals & Magazines Conferences virtual reality 2016–2018
ProQuest	877 from 905	noft(“virtual reality”) OR noft(VR) AND noft(teach*) OR noft(learn*) OR noft(educat*) AND noft(“higher education”) OR noft(“university”) OR noft(college) NOT noft(“machine learning”) NOT noft(“rehabilitation”) Limits applied Databases: All databases searched; Limited by: Full text, Peer reviewed, Date: From January 01 2016 to December 31 2018. Source type: Conference Papers & Proceedings, Scholarly Journals. Document type: Article, Conference Paper, Conference Proceeding Language: English. Automatic removal of duplications are applied.
Web of Science	112	(((TS=(“virtual reality” OR VR)) AND (TS=(educat* OR learn* OR teach* OR train*)) AND (TS=(university OR “higher education” OR college)) NOT (ALL=(“artificial intelligence” OR “neural network” OR “deep learning” OR “machine learning” OR therapy OR rehabilitation)))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)

Table B.10
List of keywords.

2d visual virtual reality system	Disease	Network security	Sport training
2d virtual reality interface	Dynamic balance control	Non-immersive virtual reality	Stroke
3d computer	Employee training	Omnidirectional video	Temporal bone
360-degree virtual reality	Gait ability	Panoramic video	Three dimensional computer graphics
Accident prevention	Gait speed	Parkinson	Treadmill training
Alzheimer’s disease	Gait training	Patient data	Upper limb
Animal health	Game performance	Personnel training	Upper limb motor training
Arm function	High school	Postural balance	Veterinary public health
Augmented reality	Mixed reality	Postural control	Video
Augmented reality exposure	Mental health	Postural stability	Virtual patient
Autism	Mixed virtual reality simulator	Primary school	Virtual reality film
Balance training	Mobile devices	Primary education	Virtual reality video
Brain injury	Mobile game	Primary education	Virtual walking
CAVE	Mobile immersive virtual reality	Radiotherapy	Virtual world
Cinematic virtual reality	Mobile learning	Rehabilitation	Virtual limb
Cognitive impairment	Motor rehabilitation	Safety engineering	Virtual reality-based rehabilitation
Cognitive deficit	Mobile robot	Secondary education	Virtual reality paradigm
Dental treatment	Mobile virtual reality	Second life	Visual speed
Desktop virtual reality	Motor disturbances	Serious game	Voice rehabilitation
Desktop vr	Muscle training	Social anxiety disorder	Vocational
Dichoptic training	National deaf–blind equipment distribution	Social stress	

documented by researchers. In other words, the validity of our conclusions is within the scope of the aforementioned research boundary—despite indications that we have chosen the timescale wisely.

Third, most papers included in this work originated from conference papers instead of journal papers, as part of our definition of immersive VR was the use of HMDs, regardless of costs. Consequently, some of the papers have not yet reported thorough solutions or lack supporting theories.

Fourth, this paper does not examine the barriers to the usage of VR for learning, as many papers have reported common issues for users, such as nausea, dizziness, and some other physical symptoms. Some barriers are related to the technology itself. For example, the display resolution and cables disturb the immersion in and control of the devices (e.g., grabbing vs. teleporting), making it difficult to switch functions. In case of mobile VR, the visual system is deemed to be demanding. Sometimes, computational issues occur during VR experiments that could cause barriers in terms of learning speed. However, technological limitations will gradually be reduced, along with the emergence of new VR technologies. The 2019 Oculus Quest, for example, comes as a cordless HMD, which will help to overcome the cable issues. Nonetheless, our work *cannot* answer the question whether a widespread use of VR in education is reasonable. None of the named limitations impairs the value of our work; in fact, they provide the opportunity to continue advancing the field.

7. Conclusion and future research

In this article, a systematic mapping study was conducted, focusing on the employment of immersive VR technologies for higher education purposes. Immersive VR technologies, application domains, learning contents, and design elements being used in recent

Table C.11
Articles included in the study.

#	Code	Authors	Title
1	P4	Veronez, Gonzaga, Bordin, Kupssinsku, Kannenberg, Duarte, et al. (2018)	RIDERS: Road inspection driver simulation
2	P5	Webster and Dues (2017)	System usability scale (SUS): Oculus Rift®DK2 and Samsung Gear VR®
3	P12	Papachristos, Vrellis, and Mikropoulos (2017)	A comparison between Oculus Rift and a low-cost smartphone VR headset: Immersive user experience and learning
4	P13	Román-Ibáñez, Pujol-López, Mora-Mora, Pertegal-Felices, and Jimeno-Morenilla (2018)	A low-cost immersive virtual reality system for teaching robotic manipulators programming
5	P15	Kwon et al. (2017)	A virtual reality based engine training system: A prototype development & evaluation
6	P16	Rosenfield et al. (2018)	AAS worldwide telescope: A seamless, cross-platform data visualization engine for astronomy research, education, and democratizing data
7	P17	Dolezal, Chmelik, and Liarokapis (2017)	An immersive virtual environment for collaborative geovisualization
8	P22	Pena and Ragan (2017)	Contextualizing construction accident reports in virtual environments for safety education
9	P23	dela Cruz and Mendoza (2018)	Design and development of virtual laboratory: A solution to the problem of laboratory setup and management of pneumatic courses in Bulacan State University College of Engineering
10	P24	Zhang, Suo, Chen, Liu, and Gao (2017)	Design and implementation of fire safety education system on campus based on virtual reality technology
11	P25	Bujdosó, Novac, and Szimkovics (2017)	Developing cognitive processes for improving inventive thinking in system development using a collaborative virtual reality system
12	P26	Hickman and Akdere (2018)	Developing intercultural competencies through virtual reality: Internet of Things applications in education and learning
13	P27	Harrington et al. (2018)	Development and evaluation of a trauma decision-making simulator in Oculus virtual reality
14	P29	Smith et al. (2018)	Effectiveness of two varying levels of virtual reality simulation
15	P38	Gerloni et al. (2018)	Immersive virtual reality for earth sciences
16	P46	Muller, Panzoli, Galaup, Lagarrigue, and Jessel (2017)	Learning mechanical engineering in a virtual workshop: A preliminary study on utilizability, utility and acceptability
17	P47	Parong and Mayer (2018)	Learning science in immersive virtual reality
18	P48	Pirker, Lesjak, and Guetl (2017)	Maroon VR: A room-scale physics laboratory experience
19	P50	Shattuck (2018)	Multiuser virtual reality environment for visualizing neuroimaging data
20	P53	Schroeder, Bailey, Johnson, and Gonzalez-Holland (2017)	Presence and usability do not directly predict procedural recall in virtual reality training
21	P54	Parmar, Isaac, Babu, D'Souza, Leonard, Jörg, Gundersen, and Daily (2016)	Programming moves: Design and evaluation of applying embodied interaction in virtual environments to enhance computational thinking in middle school students
22	P55	Zhou, Ji, Xu, and Wang (2018)	Promoting knowledge construction: A model for using Virtual Reality interaction to enhance learning
23	P56	Song and Li (2018)	Research on application of VR technology in art design teaching
24	P57	Bryan, Campbell, and Mangina (2018)	Scenic spheres—An AR/VR educational game
25	P59	Hu, Su, and He (2016)	The design and implementation of the 3D educational game based on VR headsets
26	P61	Chen (2016)	The effects of virtual reality learning environment on student cognitive and linguistic development
27	P62	Yang, Cheng, and Yang (2016)	The impact of three types of virtual reality scene on learning
28	P64	Farra, Smith, and Ulrich (2018)	The student experience with varying immersion levels of virtual reality simulation

(*continued on next page*)

Table C.11 (*continued*).

#	Code	Authors	Title
29	P66	Buń, Trojanowska, Ivanov, and Pavlenko (2018)	The use of virtual reality training application to increase the effectiveness of workshops in the field of lean manufacturing
30	P67	Zizza et al. (2019)	Toward a social virtual reality learning environment in high fidelity
31	P68	Ekkelenkamp, Koch, de Man, and Kuipers (2016)	Training and competence assessment in GI endoscopy: A systematic review
32	P71	Chin et al. (2017)	Using virtual reality for an immersive experience in the water cycle
33	P72	Němec, Fasuga, Trubač, and Kratochvíl (2017)	Using virtual reality in education
34	P73	AlAwadhi et al. (2017)	Virtual reality application for interactive and informative learning
35	P75	Carruth (2017)	Virtual reality for education and workforce training
36	P78	Ye, Hu, Zhou, Lei, and Guan (2018)	VR interactive feature of HTML5-based WebVR control laboratory by using head-mounted display
37	P79	Misbhauddin (2018)	VREdu: A framework for Interactive Immersive Lectures using virtual reality
38	P80	Cortiz and Silva (2017)	Web and virtual reality as platforms to improve online education experiences

literature on educational VR applications were examined. The review results show that the interest in immersive VR technologies for educational purposes seems to be quite high, which is indicated by the variety of the research domains that have applied this technology in teaching. The majority of authors treated VR as a promising learning tool for higher education, however, the maturity of the use of VR in higher education is still questionable. Technologies described in most of the reviewed articles remained in an experimental state and were mostly tested in terms of their performance and usability. This article also reveals that very few design-oriented studies constructed their VR applications based on a specific learning theory, which serves as technical development guidance. Moreover, few papers thoroughly describe how VR-based teaching can be adopted in the teaching curriculum.

These facts can hinder the rapid adoption of immersive VR technologies into teaching on a regular basis. We acknowledge that, in some domains such as engineering and computer science, certain VR applications have been used on a regular basis to teach certain skills, especially those that require declarative knowledge and procedural–practical knowledge. However, in most domains, VR is still experimental and its usage is not systematic or based on best practices. This paper pinpoints key gaps that serve to provide insights for future improvements, especially for VR application developers and teachers in higher education.

Our work will continue with a market analysis of VR technologies that could be employed in higher education as well with a survey of educators. We aim to continue advancing the field now that we have understood its low-maturity but nevertheless promising nature.

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Appendix A. Keyword search in each database

The employed search strings are compiled in Table A.9.

Appendix B. Keywords

An exhaustive list of keywords for deeper exclusion is given in Table B.10.

Appendix C. Selected articles

The articles included in our study are compiled in Table C.11.

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More than experience? - On the unique opportunities of virtual reality to afford a holistic experiential learning cycle

Jennifer Fromm [a], Jaziar Radianti [b], Charlotte Wehking [c], Stefan Stieglitz [a], Tim A. Majchrzak [b,*], Jan vom Brocke [c]

[a] University of Duisburg-Essen, Duisburg, Germany
[b] University of Agder, Kristiansand, Grimstad, Norway
[c] University of Liechtenstein, Vaduz, Liechtenstein

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ABSTRACT

Virtual reality has been proposed as a promising technology for higher education since the combination of immersive and interactive features enables experiential learning. However, previous studies did not distinguish between the different learning modes of the four-stage experiential learning cycle (i.e., concrete experience, reflective observation, abstract conceptualization, and active experimentation). With our study, we contribute a deeper understanding of how the unique opportunities of virtual reality can afford each of the four experiential learning modes. We conducted three design thinking workshops with interdisciplinary teams of students and lecturers. These workshops resulted in three low-fidelity virtual reality prototypes which were evaluated and refined in three student focus groups. Based on these results, we identify design elements for virtual reality applications that afford an holistic experiential learning process in higher education. We discuss the implications of our results for the selection, design, and use of educational virtual reality applications.

1. Introduction

Virtual reality (VR) generates a simulated environment through head-mounted displays (HMDs) and creates an immersive and interactive experience for users. While the entertainment and gaming industry still accounts for the largest market share, VR technology is increasingly seen as a promising opportunity to innovate online teaching and learning in higher education (Wohlgenannt, Simons, & Stieglitz, 2020). The global VR market is projected to reach a market size of 120.5 billion US dollars until 2026 and the adoption of VR is expected to witness fast growth in the education industry (Fortune Business Insights, 2019). According to previous research, the opportunity to create learning experiences that would otherwise not be possible in the real life classroom represents the most important motivation to use VR in education (Freina & Ott, 2015). A recent study supports the notion that experiential learning through VR is indeed possible and also effective in terms of learning outcomes (Kwon, 2019). Many other studies highlighted the potential of VR technology to afford experiential learning (Aiello, D'Elia, Di Tore, & Sibilio, 2012; Gouveia, Lopes, & De Carvalho, 2011; Jarmon, Traphagan, Mayrath, & Trivedi, 2009; Le, Pedro, & Park, 2015; San Chee, 2001; Su & Cheng, 2019).

However, we found that most of these emphasize the learning mode of concrete experience, although experiential learning does not only consist of *experience* as the name suggests. According to experiential learning theory, students cycle through the four different learning modes of concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984). Furthermore, most of these studies focused on virtual worlds (e.g., Second Life) and therefore did not consider the technological advancements in the meantime. Thus, the open question remains whether VR only affords the learning mode of concrete experience or whether the technology also provides unique opportunities to afford the remaining three learning modes. In addition, a systematic literature review of VR studies in higher education revealed that most design-oriented studies lack a foundation in learning theory (Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020). As a result, the majority of educational VR applications are designed with a specific *learning outcome* in mind but do not aim at supporting a specific *learning process* such as experiential learning. Some recent studies started to address this research gap by grounding the design of educational VR applications in learning theories such as

* Corresponding author.
E-mail address: timam@uia.no (T.A. Majchrzak).

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constructivism (Kim et al., 2020), the peer assessment learning approach (Chang, Hsu, & Jong, 2020), or inquiry-based learning (Jong, Tsai, Xie, & Kwan-Kit Wong, 2020; Petersen, Klingenberg, Mayer, & Makransky, 2020). We aim to contribute to this line of research and identify VR design elements that can be implemented to afford a holistic experiential learning process. Hence, we ask the following research question:

RQ: How can educational VR applications be designed to afford the four experiential learning modes (i.e., concrete experience, reflective observation, abstract conceptualization, active experimentation)?

To answer this question, we followed a user-centered design approach and conducted three design thinking workshops with interdisciplinary teams of lecturers and students. Afterward, we evaluated and refined the designed VR prototypes in three focus groups with students. The results of the workshops and focus groups were analyzed through an experiential learning and affordance lens. With our study, we contribute a deeper understanding of how the unique opportunities of VR technology afford a holistic experiential learning cycle.

The remainder of this article is structured as follows: In Section 2, we provide the theoretical background of our study and summarize previous work about VR in higher education, experiential learning, and affordance theory in the field of education science. Then, we describe how we conducted and analyzed the design thinking workshops and focus groups in Section 3. In Section 4, we present detailed results from the workshops followed by detailed insights from the focus groups in Section 5. We then derive design principles from our findings and discuss these in light of previous research in Section 6. In Section 7, we conclude with a summary of our key results, the limitations of our study, and avenues for future research.

2. Theoretical background

2.1. Virtual reality in higher education

Biocca & Delaney (1995, p. 63) define VR as *"the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment"*. Previous research suggested that VR enables users to experience a higher degree of immersion, interactivity, and presence than other information systems (Walsh & Pawlowski, 2002). There are systematic studies that provide an overview of VR use for education and training (e.g., Chavez & Bayona, 2018; Feng, González, Amor, Lovreglio, & Cabrera-Guerrero, 2018; Radianti et al., 2020; Suh & Prophet, 2018; Wang, Wu, Wang, Chi, & Wang, 2018; Wohlgenannt, Fromm, Stieglitz, Radianti, & Majchrzak, 2019). In general, they concur that VR is a promising approach to support higher education. However, only recently scholars began to discuss VR design elements for higher education, supported by solid learning theories that assure effective learning outcomes. Wang et al. (2018) examined various works concerning the use of VR for training in construction engineering. The authors concluded that VR is suitable for a flipped classroom and ubiquitous learning activities. They underlined that educational VR kits need to consider emerging education paradigms. Chavez and Bayona (2018) emphasized the essential VR characteristics that determine positive learning effects such as interactive capability, immersion interfaces, animation routines, movement, and simulated virtual environments. Overall, the authors revealed seventeen positive effects of VR-supported learning, ranging from improved learning outcomes, increased learning motivation and learning interest to the possibility of enabling learning through "live experience". Suh and Prophet (2018) identified the theoretical foundations applied in educational VR studies. However, the authors did not focus on how these learning theories can be used as a basis for educational VR design and development. Feng et al. (2018) focused on VR applications for evacuation training and carried out an extensive analysis of the VR learning outcomes, covering both pedagogical and behavioral impacts. Suh and Prophet (2018) and Feng et al. (2018), however, neither provided suggestions on how learning theories can inform the design process, nor identified which learning theories would enhance the learning outcomes from the literature under study.

A literature review about the use of VR for the design of educational virtual environments also revealed that learning theories are often implied but seldom explicitly mentioned (Mikropoulos & Natsis, 2011). As a response, Fowler (2015) introduced the "design for learning" perspective and argued that an understanding of pedagogical underpinnings should inform the design of educational VR applications. More recently, Radianti et al. (2020) and Wohlgenannt et al. (2019) conducted an extensive survey of the literature in the area of immersive VR for higher education. Radianti et al. (2020) reviewed literature published between 2016 and 2019 and identified the applied learning theories as well as the application domains, design elements, and learning outcomes of VR applications for higher education. The authors identified fourteen VR design elements and mapped these to different learning outcomes. However, the study revealed that the majority of design-oriented immersive VR studies under review did not explicitly mention a learning theory as foundation for the development of educational VR applications. When broadening our scope beyond higher education, we found that scholars more frequently elaborated on how learning theories guided the design and evaluation of educational VR applications. For instance, Chang et al. (2020) introduced the peer assessment learning approach triggering better learning achievement, self-efficacy, and critical thinking. The study is based on a solid learning theory, which served as guidance for the design process of VR learning activities. Kim et al. (2020) used the constructivist learning approach as theoretical underpinning for the development of an immersive VR app for gardener apprentices. Jong et al. (2020) proposed a pedagogical framework (LIVIE) that provides guidance on how to leverage immersive VR apps for geography education based on the inquiry-based learning model. In a similar fashion, Petersen et al. (2020) developed and evaluated immersive VR field trips guided by inquiry-based learning theory. In both studies, the design and evaluation of the VR learning activities were grounded in solid learning theories. Following this stream of research, the experiential learning theory will guide our qualitative design-oriented study.

2.2. Experiential learning theory

Kolb (1984) defined the theory of experiential learning based on several fundamental models of experiential learning, including Lewin, Dewey, and Piaget, which basically refer to *learning from experience* or *learning by doing*. Learners immerse in a particular experience and reflect their experiences to develop new skills, attitudes, or ways of thinking (Lewis & Williams, 1994). Experiential learning is defined as *"the process whereby knowledge is created through the transformation of experience. Knowledge results from combination of grasping and transforming experience"* (Kolb, 1984, p. 41). The theory of experiential learning builds on *six propositions* (Kolb, 1984). First, learning is a process and not an outcome. The process shall be accompanied by feedback. Second, learning always includes relearning. Learners' beliefs of a particular topic are challenged and tested with new ideas and insights. Third, the learning process is driven by conflicts, differences, or disagreements. By resolving conflicts or discussing disagreements the individuals learn. Fourth, learning is adapting to the environment by feeling, thinking, perceiving, and behaving in a certain way. Fifth, learning results from assimilating new experiences to existing concepts and vice versa (i.e., synergetic transaction). Finally, the learners create new knowledge. Based on these six propositions and to acquire new skills, attitudes, or knowledge, learners need to confront *four modes of experiential learning*. The learning modes include two opposing modes of grasping experiences and two opposing modes of transforming experiences. Grasping experience includes *Concrete Experience* and *Abstract Conceptualization*, whereas transforming experiences refers to *Reflective Observation* and *Active Experimentation*. These learning modes occur in a four-stage cycle. First, learners have concrete experiences. They involve themselves in a new situation with an open mind and without any bias. Second, learners reflect on and observe these experiences from several perspectives. Third, the learners engage in abstract conceptualization. They are able to transform their observations in theory by creating concepts that are generalizations or principles that are logical. Fourth, learners make use of their developed theories to solve a given problem. These theories serve as guidance for learners to engage into action by testing what they learned in complex situations. After the learners actively experimented with their new learning, the process restarts.

The theory of experiential learning has been increasingly associated with digital technologies in general, but also with VR in specific. For instance, studies focused on the integration of experiential learning into online classes to elaborate skills and competences that are helpful for the connection of experience and communication technologies (Baasanjav, 2013) or investigated the role experience plays in e-learning from simple content sharing to direct experience and action learning (Carver, King, Hannum, & Fowler, 2007). With regard to VR studies, the theory of experiential learning is one of the most widely applied learning theories for VR-enabled learning (Li, Ip, & Ma, 2019). Bricken (1990), for instance, advocated the use of VR as a tool for experiential learning as it supports learners to apply knowledge and experience consequences. Bell and Fogler (1997), San Chee (2001), and Chen, Toh, and Ismail (2005) pointed out that VR accommodates the experiential learning theory, as it allows students to explore, experience, and examine their environments freely, even hazardous and inaccessible locations such as operating nuclear reactors or microscopic pores. San Chee (2001) grounded the development of an interactive, collaborative virtual learning environment on Kolb's experiential learning framework to obtain concrete learning experiences through active experimentation. Students can learn by making sense of observations as well as problem solving and coordinated joint activities in the virtual world. Studies from different research fields (e.g., education, medicine) advocated the potential of VR as this technology allows the inducement of interactivity (Sultan et al., 2019). VR provides a rich and engaging education context that supports experiential learning as students can experience learning by doing. This raises interest and motivation which effectively supports knowledge retention and skills acquisition (Sultan et al., 2019). Using VR in teaching encourages a more concrete experiential mode of learning from the students (Wang, Newton, & Lowe, 2015) and reflective observation in a safe and authentic environment (Li et al., 2019). Further, first small attempts have been made which focus on the design of VR learning scenarios or learning content, especially for children with autism spectrum disorder (Li et al., 2019).

Experiential learning theory received criticism from various researchers (e.g., Garner, 2000; Morris, 2019). Researchers raised questions concerning a lack of theoretical foundations, a lack of clarity, or conceptual weaknesses. For instance, some researchers argued that experiential learning theory lacks theoretical and empirical foundations including the instruments validity to measure learning style or the model's logic itself (Coffield, Moseley, Hall, & Ecclestone, 2004; Garner, 2000; Hawk & Shah, 2007). They questioned whether Kolb's work could reliably describe an individual's learning style. Further, De Ciantis and Kirton (1996) maintained that Kolb's learning styles in fact define a learning process rather than a style. Additionally, Morris (2019) was concerned about a lack of clarity regarding what "concrete experience" exactly constitutes and how educators can interpret the meaning of it. Despite the criticism, many researchers advocated and positively reported on Kolb's work (Garner, 2000), as this theory considers a holistic view of learning on the combination of experience, perception, cognition, and behavior (Kolb, 1984). Kolb's work is probably the *"most scholarly influential and cited model"* regarding learning theory (Morris, 2019) and has been successfully applied in multiple research fields (e.g., business, engineering, medicine) including the field of VR (Li et al., 2019). Thus, we consider this theory suitable as our theoretical foundation.

2.3. Affordance theory in education science

The notion of affordances has its origin in ecological psychology and was introduced by James J. Gibson who questioned existing assumptions about visual perception (Gibson, 1979). He challenged the traditional assumption that animals including humans first perceive physical properties of their environment and then deduce the interaction possibilities offered to them. Instead, he assumed that animals and humans directly perceive the action potential of their environment meaning *"what it offers [...], what it provides or furnishes, either for good or ill"* (Gibson, 1979, p. 197). In his view, the physical properties of surfaces, substances, objects, and other animals in the environment determine the offered affordances to a certain extent, however, affordances are also unique for each species or even for different members of the same species (Gibson, 1979).

The affordance concept has been adopted in the field of information systems, studying the design, use and impact of information technology (Dremel, Herterich, Wulf, & Vom Brocke, 2020; Lehrer, Wieneke, Vom Brocke, Jung, & Seidel, 2018; Seidel, Recker, & Vom Brocke, 2013) as well as in education science as a theoretical foundation for the selection and design of e-learning technologies (Antonenko, Dawson, & Sahay, 2017; Bower, 2008; Kirschner, Strijbos, Kreijns, & Beers, 2004). While traditional instructional design approaches assume a causal relationship between technology, instructional methods, and *learning outcomes*, the affordance concept allows designers to focus on promoting a certain kind of *learning behavior* (Strijbos, Martens, & Jochems, 2004). For example, Kirschner et al. (2004) suggested that e-learning environments should offer certain educational, social, and technological affordances to enable the emergence of collaborative learning processes. Furthermore, Bower (2008) developed an affordance-based methodology that allows educational designers to match the affordance requirements of learning tasks with the provided affordances of available e-learning technologies. In a similar fashion, Antonenko et al. (2017) proposed an affordance-based design process that emphasizes the alignment of user needs with the affordances of educational technologies.

Meanwhile, affordance studies in education science have investigated the educational affordances of various technologies such as social media (Manca, 2020), wikis (Fu, Chu, & Kang, 2013), mobile computing (Tang & Hew, 2017), wearables (Bower & Sturman, 2015), learning management systems (Rubin, Fernandes, & Avgerinou, 2013), and Web 2.0 (Augustsson, 2010). There also have been several studies that identified the educational affordances of VR, however, these focused on virtual worlds such as Second Life and Active Worlds (Dalgarno & Lee, 2010; Dickey, 2003, 2005; Gamage, Tretiakov, & Crump, 2011; Shin, 2017). In the meantime, VR technology has evolved and there are consumer-friendly standalone headsets on the market (e.g., Oculus Quest) that allow a higher degree of immersion and interactivity than the aforementioned desktop-based VR worlds. In previous studies, VR has often been described as promising to support experiential learning processes (Aiello et al., 2012; Gouveia et al., 2011; Jarmon et al., 2009; Le et al., 2015; San Chee, 2001; Su & Cheng, 2019). However, we still require a deeper understanding of VR technologies' unique educational affordances that enable the emergence of experiential learning processes.

3. Research design

3.1. Design thinking workshops

In the context of e-learning, workshops have been proposed as a research methodology that allows researchers to identify factors that are not obvious to either the participants or the researchers advancing the meaning negotiation between them (Ørngreen & Levinsen, 2017). Hence, we conducted workshops following the user-centered innovation approach of design thinking. This innovation approach has become increasingly established in practice for the development of products, services, and processes, as the resulting innovations are not only technologically feasible and viable for the business, but also focus on the users' needs and problems (Brown et al., 2008). The early integration of future users into the design process and the development of a deep understanding of their problems and needs is of great importance; not only in business. Successful design thinking is characterized by three essential elements: 1. design thinking mindset, 2. process, and 3. methods (Brenner, Uebernickel, & Abrell, 2016). The design thinking mindset forms the framework for the entire process and includes aspects such as user centricity, co-creativity, and interdisciplinarity (Carlgren, Elmquist, & Rauth, 2016).

In education science, researchers most often discussed pedagogical strategies to promote design thinking as a valuable 21st century skill enabling students to solve complex problems in their future work lives (e.g., de Figueiredo, 2020; Linton & Klinton, 2019; Razzouk & Shute, 2012; Scheer, Noweski, & Meinel, 2012). However, design thinking has also been proposed as a valid research method for design-oriented studies in the field of information systems (Devitt & Robbins, 2012; Dolak, Uebernickel, & Brenner, 2013). In this field, many design-oriented researchers follow the established design science research paradigm which aims at the development and evaluation of an *"IT artifact created to address an important organizational problem"* (Hevner, March, Park, & Ram, 2004). The design science research paradigm provides a research process model (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007) and seven research guidelines (Hevner et al., 2004). Furthermore, design science research consists of three research cycles: The relevance cycle bridges the application domain with the design activities; the design cycle includes artifact building and evaluation activities; and the rigor cycle connects design activities with the existing knowledge base (Hevner, 2007). Dolak et al. (2013) found that design thinking fulfills the design science research guidelines but expressed concerns about a lack of rigor during the design evaluation process. While the design science research paradigm provides guidance on how to establish rigor in design-oriented research, the human-centered nature of design thinking can enrich the relevance cycle (Dolak et al., 2013; Hevner, 2007). As a result, they argue for the extension of design science research through design thinking and vice versa (Dolak et al., 2013). Another comparative study described design science and design thinking as complementary research paradigms which are both equally viable depending on the problem area (Devitt & Robbins, 2012). The authors describe design thinking as well suited for wicked, ill-defined problem areas which require stakeholder understanding, empathy, creativity, and co-creation to bring radical innovations to market or application context (Devitt & Robbins, 2012). Wicked problems are complex because various stakeholders have different views on what the actual problem is and how a solution could look like; at the same time the problem evolves dynamically and the solution of today might not be the solution of tomorrow (Rittel & Webber, 1973). Borko, Whitcomb, and Liston (2009) recognize teaching and learning with emerging technologies as a wicked problem: *"The rapid growth of digital technologies, coupled with the complexity of classroom life, increases both the potential transformative power and the difficulty of problems associated with incorporating innovative technologies in teaching."* Therefore, we deemed design thinking an appropriate research paradigm for our study. To address the concerns about a lack of rigor in design evaluation, we combined design thinking workshops with focus groups as an established method for design evaluation and refinement (Tremblay, Hevner, & Berndt, 2010). In recent literature, further examples of studies that applied design thinking in design-oriented research can be found (e.g., Fromm, Mirbabaie, & Stieglitz, 2019; Grobler & De Villiers, 2017; Przybilla, Klinker, Wiesche, & Krcmar, 2018). Various phase models exist for conducting design thinking workshops, with Fig. 1 illustrating the widespread design thinking process developed by Plattner, Meinel, and Weinberg (2009).

To move from a problem to a solution space, the design thinking process includes six interrelated steps: understand, observe, define, ideate, prototype, and test. The *understand step* involves creating a common understanding of the design challenge. The *observe step* involves empathizing with users and understanding their needs and problems in their everyday environment based on surveys, interviews or observations. The *define step* involves consolidating the collected information to one main design objective with the help of methods such as point-of-view-statements or developing personas. A persona represents the target person whose problems will be solved. The *ideate step* involves generating and selecting suitable solution ideas based on methods such as brainstorming. The *prototype step* includes making the solution ideas tangible and experienceable based on low fidelity prototypes, role plays, or storytelling. Finally, the *test step* involves evaluating the prototypes with the target group to receive feedback with the help of interviews and refine the prototype.

3.1.1. Participants

The goal of the workshops was to identify the learning challenges perceived by students, assess their needs, and to develop innovative VR solutions fostering experiential learning processes. Hence, we conducted three design thinking workshops with interdisciplinary teams of lecturers and students from various fields. The participants were recruited by personal request of the authors. Table 1 gives an overview of the workshop participants. We took care to recruit participants from different disciplines for the workshops. An interest in technology-supported learning was communicated as a requirement for participation, whereas prior knowledge or experience with VR technologies was not required. All three workshops were moderated by a professionally trained design thinking coach.

3.1.2. Workshop procedure

All participants had the opportunity to familiarize themselves with the VR technology (i.e., HTC Vive) prior to the workshop. They were

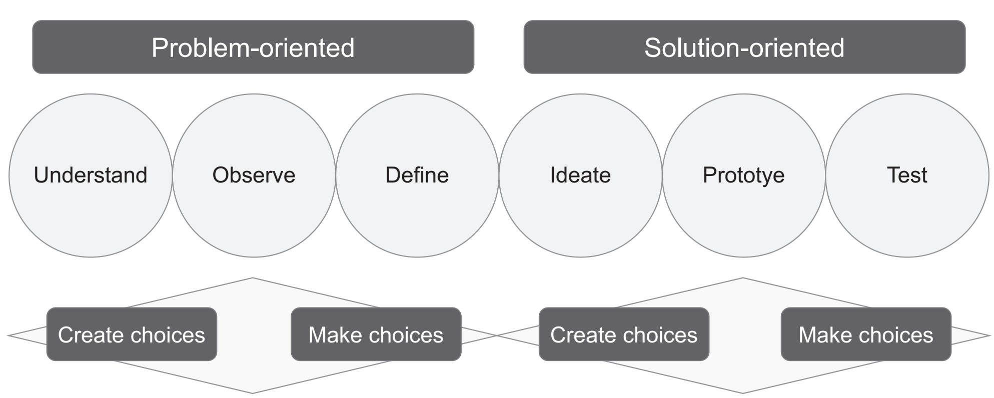

Fig. 1. Design thinking process. Adapted from Plattner et al. (2009).

Table 1
Design thinking workshop participants.

Workshop	Gender	Role	Department/study program
1	Female	Lecturer	Architecture
1	Female	Lecturer	Information systems
1	Female	Lecturer	Media science
1	Female	Lecturer	Architecture
1	Female	Lecturer	Information and communication technologies
1	Male	Lecturer	Business administration
1	Male	Lecturer	Information systems
1	Female	Student	Information systems
1	Male	Student	Business administration
1	Male	Student	Business administration
2	Female	Lecturer	E-learning
2	Female	Lecturer	Mathematics
2	Male	Lecturer	Information systems
2	Male	Lecturer	Mathematics
2	Male	Lecturer	Information systems
2	Female	Student	Media science
2	Female	Student	Media science
2	Male	Student	Media science
3	Female	Lecturer	Information systems
3	Female	Lecturer	Education science
3	Female	Lecturer	Information and communication technologies
3	Female	Lecturer	Media science
3	Male	Lecturer	Information systems
3	Male	Lecturer	Information systems
3	Male	Lecturer	Information systems
3	Female	Student	Information systems
3	Male	Student	Information systems

able to try out various VR applications (e.g., The Lab, Google Blocks). The design thinking coach explained all central elements (i.e., mindset, process, and methods) and afterward he presented the design challenge, which was developed in advance by the authors in collaboration with the design thinking coach (i.e., *How can VR technologies support an experiential learning process for students in higher education?*).

The workshop participants followed the six-step design thinking process of Plattner et al. (2009). In the *understand step*, the participants derived a common group understanding of the challenge by discussing the design question. In the *observe step*, the participants created an interview guide and interviewed students in their everyday settings around the university campus (e.g., library, cafeteria). The interviews concentrated on the students' current learning habits, tools used, perceived learning challenges, and their ideas about learning in the future. In the *define step*, the participants presented these insights to their team members and grouped all insights into meaningful clusters. One participant presented the results of an interview, while the other participants listened and used sticky notes to note the key findings on each person interviewed. These were then placed on a whiteboard and sorted into the predefined categories goals, activities/tasks, pain points, observations and artifacts/tools. Based on these categories the participants created a persona. The personas were fictitious students including name, age, study program, hobbies, interests, learning goals, habits, problems, and needs.

In the *ideate step*, the participants took part in a rapid brainstorming session. For example, the participants wrote down ideas for suitable hardware, specific software functionalities, and the interface design of a VR solution for the students' problems. The participants presented their ideas to each other and clustered their solution ideas. The participants then selected a "safe bet", "most meaningful" and "longshot" idea. A safe bet idea is a less original and at the same time technologically feasible idea, while a longshot idea is very original, but may only be technologically feasible in the future. The implementation of a most meaningful idea, on the other hand, would make the biggest difference for the target group. When selecting the most meaningful idea, participants were asked not to consider the technological feasibility of the idea in their evaluation. After the voting process, the participants selected their most meaningful idea for a prototype implementation. In the *prototype step*, the participants were able to choose their favorite method to make their selected solution idea tangible. The participants prepared a role play, a storyboard made of writable scene boards or a tangible prototype made of handicraft materials (e.g., cardboard and aluminum foil). At the end of the workshop, the participants presented their prototypes and it was discussed to what extent the presented idea was suitable to solve the identified problems of the students and could support an experiential learning process. Especially the student participants as part of the target group gave valuable feedback.

3.1.3. Documentation of workshop results

The design thinking coach informed the participants about the documentation of the results and obtained their oral consent. The participants were encouraged to write their thoughts down continuously and arrange them on their flip charts. The co-authors followed the groups as passive observers and took notes and photos of the flip charts to document the results of each process step (Darsø, 2001). The presentation and discussion of the prototypes were video recorded and transcribed following the rules of Kuckartz (2012). Afterward, one author created a description of the developed personas, point of view statements and prototypes based on the transcripts, photos, and notes. Upon request, at least one participant from each design thinking workshop agreed to review the descriptions. The descriptions were then supplemented with the comments of the participants. This ensured that the descriptions in the results section actually reflected the thoughts of the workshop participants.

3.2. Focus group discussions

After the design thinking workshops, we conducted three student focus group discussions. A focus group is defined as a moderated discussion among a group of people who discuss a topic under the direction of a facilitator whose role is to promote interaction and keep the discussion on the topic of interest (Stewart, Shamdasani, & Rook, 2007). The aim of the focus group discussions was twofold: 1. evaluation and 2. refinement of the developed prototypes. The focus group method has its origin in social research, however, Tremblay et al. (2010) proposed focus groups as a valid method for artifact evaluation and refinement in design research. Meanwhile, focus groups are commonly used in design research (e.g., Gibson & Arnott, 2007; Lins, Schneider, Szefer, Ibraheem, & Sunyaev, 2019; Niemöller, Metzger, & Thomas, 2017).

3.3. Participants

In each of the three workshops, the participants developed ideas for VR applications that were aimed at students of different study programs depending on the students they interviewed during the workshops. The prototype developed in the first workshop addressed the needs of business administration students, while the participants of the second workshop focused on the needs of media science students, and the participants of the third workshop developed a VR solution for students in the field of education science. In the composition of the focus groups, care was taken to select students from these respective study programs. In addition, we invited media science students to include some participants with VR experience in each group. Table 2 gives an overview of the focus group participants.

3.3.1. Focus group procedure

Before conducting the focus groups, we developed a facilitator guide to set the agenda for the focus group discussions. The facilitator guide was structured following the guidelines from Krueger (2014). The focus group discussion took place in a meeting room that was equipped with a large round table, a whiteboard, and recording equipment. During the focus groups, the facilitator guided the participants and encouraged everyone to participate in the discussion while being open, honest, and respectful to each other. To provide a basis for discussion, the facilitator

Table 2
Focus group participants.

Group	Age	Gender	Study program	VR experience
A	19	Female	BA media science	Participated in VR studies
A	18	Female	BA business administration	*None*
A	22	Female	BA Business administration	Watched VR Let's Play videos
A	20	Female	BA media science	Played VR games
B	19	Male	BA media science	Owns VR headset; Played VR games
B	22	Female	BA media science	Participated in VR studies
B	18	Female	BA media science	Played VR games; watched VR Let's Play videos
B	27	Male	MA media science	Participated in VR studies; visited a holo café; Owns mobile VR headset
B	28	Female	MA media science	Participated in VR studies
B	20	Female	BA media science	Participated in VR studies
C	25	Female	MA media science	Played a VR game once
C	26	Female	MA media science	Participated in VR studies; tried out VR at a trade fair
C	19	Male	BA education science	*None*
C	20	Female	BA education science	*None*
C	22	Female	BA education science	*None*
C	24	Female	BA media science	Participated in VR studies; developed a VR app in a university course
C	21	Female	BA media science	Participated in VR studies; developed a VR app in a university course

presented one persona and prototype developed in the workshops using the descriptions that were created based on the workshop documentation. Another author served as assistant to observe the discussion and take notes. The discussions were audio recorded with the consent of the participants and the recordings were transcribed according to the rules of Kuckartz (2012). On average, the focus group discussions lasted two hours. Table 3 outlines the structure and content of the focus group discussions as described in the facilitator guide.

3.3.2. Analysis of workshop and focus group results

In our analysis, we included the prototype descriptions resulting from the workshops and the transcripts from the focus group discussions. To analyze the text material, we conducted a qualitative content analysis applying the method of deductive category assignment (Mayring, 2014). In the following, we explain how we implemented each step of the deductive category formation. *Definition of research question and theoretical background:* We formulated a clear research question (see Section 1) and described our theoretical background of experiential learning and affordance theory (see Section 2). *Definition of the category system:* From our research question, we defined two main categories before the coding process (i.e., VR design elements, experiential learning affordances). Based on a recent systematic literature review about VR in higher education (Radianti et al., 2020), we defined fourteen sub categories of VR design elements (i.e., realistic surroundings, passive observation, moving around, basic interaction with objects, assembling objects, interaction with other users, role management, screen sharing, user-generated content, instructions, feedback, knowledge test, virtual rewards, and making meaningful choices). Informed by experiential learning theory and affordance theory, we defined four sub categories of experiential learning affordances (i.e., concrete experience affordance, reflective observation affordance, abstract conceptualization affordances, active experimentation affordance). *Definition of the coding guideline:* We created a table with the four columns category label, category definition, anchor example, and coding rule as a coding guideline (see Table 9 and Table 10 in the Appendix). Before the coding process, we

Table 3
Focus group procedure.

Structure	Content of the focus group discussion	Duration
Introductory stage	The facilitator greeted the participants, provided them with a nameplate and presented the purpose of the focus groups. The facilitator informed the participants about the focus group procedure and their rights as participants. The participants filled out a short questionnaire to collect sociodemographic data and signed the declaration of consent. The participants were asked to introduce themselves and tell the others about their study program, VR experience, and motivation to take part in the focus group.	25 mins
Transition stage	The facilitator presented one of the personas developed in the workshops and asked the participants how much they can identify with the persona and what differences they see between themselves and the persona. The participants discussed their learning habits, challenges and needs compared to the presented persona.	10 mins
In-depth investigation (part 1)	The facilitator presented one of the prototype developed in the workshops and asked the participants to discuss the usefulness of the prototype: What is your first impression of the prototype? How could the prototype help you to learn? How useful do you find the application? What do you like about the prototype? What do you not like about the prototype? What would keep you from using the prototype?	30 mins
In-depth investigation (part 2)	The facilitator asked the participants to discuss how they would extend or change the prototype to support an experiential learning process. While refining the prototype the participants should think about questions such as: What could the virtual environment look like? What could the technology enable you to do? What action potentials does your technology offer? How does the technology help you with your learning activities? How does the technology help you with your learning activities? The participants presented their refined prototype.	50 mins
Closure	The facilitator summarized the most important aspects of the discussion and asked the participants if they have any further questions or ideas.	5 mins

filled in the category labels and category definitions derived from previous research and our theoretical background. *Preliminary coding:* Three authors started to code the material independently from each other. When the authors found a text passage fulfilling a category definition, the category label was assigned to this text passage. During this trial run-through, the authors also added text passages as anchor examples and coding rules to the coding guideline. *Revision of the categories and coding guideline:* After the trial run-through was completed, the authors discussed their discrepancies until they reached agreement and revised the coding guideline. They decided to adjust the category labels of some VR design elements to distinguish more clearly between design elements and affordances as action potentials (1. moving around was changed to character movement and 2. making meaningful choices was changed to realistic scenario). Furthermore, the coders did not found an anchor example for every VR design element proposed by Radianti et al. (2020). It was therefore decided to remove these sub categories from the coding guideline. However, we also added a new design element labeled interaction with intelligent agents to the original framework of Radianti et al. (2020). In previous literature, an agent has been defined as *"a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives"* (Wooldridge, 2009). To be intelligent, an agent further has to be reactive, proactive and social (Wooldridge, 2009). We define the VR design element interaction with intelligent agents as follows: *Students can interact with intelligent agents that have a visual representation. The intelligent agents are able to process the speech and body language of the students, analyze how well they perform a certain skill and show a realistic reaction. For example, if a student practices presentation skills in front of an intelligent agent, the agent reacts with changing facial expressions based on the student's performance (*e.g. *bored* vs. *excited expression)*. Furthermore, we revised the coding rules of the experiential learning affordances, in particular, to distinguish more clearly between the reflective observation and abstract conceptualization categories. The final coding guideline can be found in the Appendix. *Final working through the material:* The three authors conducted a second round of coding with the revised coding guidelines and resolved their few remaining discrepancies through a discussion at the end. *Analysis:* We used the Code-Relations-Browser in MAXQDA to analyze which categories were assigned to text passages in close vicinity. This allowed us to create a systematic mapping of VR design elements that were associated with specific experiential learning affordances (see Table 8 in Section 6).

4. Workshop results

4.1. Personas and student needs

The workshops resulted in three personas that represent common characteristics of the interviewed students and served as a basis for the user-centered design process. For example, some students spent a lot of time at university to visit lectures and meet with learning groups (*Giselle*). Other students worked a few hours per week but still prioritized their studies and visited most lectures (*Marcel*). A few students were working part-time and wanted to complete their studies soon, so that they could start working full-time (*Pascal*). Furthermore, students differed in their preference for individual learning (*Pascal*) and group learning (*Marcel, Giselle*). For individual learners, it was difficult to stay focused because they were often distracted by their phones (*Pascal*). Many students with a preference for group learning needed time to reflect on learning content and wished for opportunities to discuss with other students (*Marcel, Giselle*). Furthermore, they often did not feel prepared for their future career and were bored with lectures that require them to memorize a lot of facts (*Marcel, Giselle*). Instead, they wished for practice-oriented content and opportunities to experience real-life situations (*Marcel, Giselle*). In summary, students demanded space for conversational learning, acting, and reflecting as it is suggested by experiential learning theory. Table 4 provides an overview about the developed personas.

4.2. VR prototypes and experiential learning affordances

Based on the personas, the workshop participants developed three prototypical ideas for VR applications that afford experiential learning. The prototypes were presented in the form of a roleplay and address the needs of the business administration student Pascal, the media science student Marcel, and the education science student Giselle. Tables 5, 6 and 7 (following on pages 7 to 8 along with an explanation) summarize each prototype's design elements and their experiential learning affordances.

VR Business Pitch (Table 5) enables Pascal to practice a business pitch in a safe environment in front of a virtual manager. When Pascal starts the application, he is welcomed by a virtual instructor. Pascal is teleported into a virtual meeting room and has the possibility to present slides he has prepared in advance. An intelligent agent dressed like a manager listens and provides live feedback through simulated facial expressions (e.g., bored or excited). Based on his performance, the virtual instructor provides Pascal with feedback on his performance and recommends a video from an integrated media library that helps him to improve individual weaknesses.

VR Tweet Emergency Team (Table 6) illustrates how a VR case study can supplement a theoretical lecture about social media analytics. Together with other students, Marcel experiences a realistic emergency scenario and must decide where emergency forces should be sent on the basis of tweets. The VR application allows to access additional information about tweets. The students are also able to perform a 3D network analysis, which allows to visualize the tweet authors' position in the network. Altogether, this information allows conclusions about the relevance of the content and the author's credibility which helps to decide whether emergency forces should be sent. The VR case study enables Marcel to gain a better understanding of social media analytics in a practice-oriented way. Working with other students on a realistic case prepares Marcel for a potential career. For him, learning in an immersive environment is also a welcome alternative to memorizing the contents of lecture slides.

VR Classroom Simulator (Table 7) allows Giselle to experience realistic teaching scenarios that enable her to prepare for difficult situations in the classroom. The application offers a large database of realistic scenarios created by recording 360° videos of thousands of real lessons. When starting the application, Giselle receives a scenario suggested by an intelligent agent and can observe the real course of a lesson from the teacher's point of view. Critical situations are recognized by the intelligent agent and Giselle is asked how she would react (e.g., if a student insulted another student). The intelligent agent provides multiple choice options, evaluates the answer and selects a suitable 360° video from the database to continue the scenario. Thus, Giselle influences the outcome of the scenario and becomes aware of the consequences of her decisions in the real classroom. After she completed a scenario, Giselle can enter a VR meeting room to reflect on her experience and discuss her performance with other students.

Table 4
Overview about personas.

	1st Persona Pascal	2nd Persona Marcel	3rd Persona Giselle
Age	21 years	23 years	24 years
Study program	Business administration	Media science	Education science
Job	Consultant (part-time)	Research assistant (six hours/week)	None
Location	Lives and works in the same city, commutes to university	Lives, studies, and works in the same city	Lives and studies abroad (international exchange student)
Learning habits	Summarizes contents of lecture slides, studies on the train	Enjoys learning in groups, likes to discuss content with other students	Enjoys learning in groups, likes to discuss content with other students
Learning challenges	Often distracted by his mobile phone, not much time for his studies because of his part-time job	Dislikes memorizing the content of lecture slides, quickly forgets facts after exams, feels unprepared for his future job	Cannot stay focused during lectures without interactive sessions, not enough breaks to reflect on learning content during lectures, feels unprepared for her future job
Student needs	Needs a solution to focus on his studies, needs a solution that allows him to study time-efficiently	Needs practice-oriented learning content, needs a collaborative solution	Needs a solution to focus on her studies, Needs practice-oriented learning content, Needs a collaborative solution, Needs breaks and short learning sessions

Table 5
VR business pitch: design elements and experiential learning affordances.

Learning mode	Design element	Experiential learning affordance
Concrete experience	Realistic surroundings (virtual meeting room) Interaction with intelligent agents (realistic facial expressions)	Pascal can experience how it feels like to pitch a business idea in front of a decision-maker; Pascal can experience how it feels like to receive unpleasant reactions during a pitch
Reflective observation	Feedback (report from virtual instructor) Interaction with intelligent agents (realistic facial expressions)	Pascal can observe the reactions of the intelligent agent and reflect how convincingly he presents
Abstract conceptualization	Instructions (video recommendations)	Pascal can analyze how he could transform the theoretical explanations from the videos in his presentation practice
Active experimentation	Immediate feedback (report from virtual instructor) Interaction with intelligent agents (realistic facial expressions)	Pascal can try different presentation techniques to change the facial expression from the intelligent agent

Table 6
VR tweet emergency team: design elements and experiential learning affordances.

Learning mode	Design element	Experiential learning affordance
Concrete experience	Realistic surroundings (virtual emergency room) Realistic scenario (different crisis scenarios) Interaction with other users (group decision-making)	Marcel can experience how it feels like to be part of an emergency management team that has to make difficult decisions under time pressure; Marcel can experience how the consequences of his decisions feel like
Reflective observation	Realistic scenario (different endings based on decision)	Marcel can observe how the scenario unfolds based on the team decision and reflect about their analysis approach and decision-making performance
Abstract conceptualization	–	–
Active experimentation	Realistic scenario (different crisis scenarios) Basic interaction with objects (interaction with tweets and social network)	Marcel can try different social media analysis techniques and see how this changes the outcome of the scenario

Table 7
VR classroom simulator: design elements and experiential learning affordances.

Learning mode	Design element	Experiential learning affordance
Concrete experience	Realistic surroundings (virtual classroom) Realistic scenario (different teaching situations) Interaction with intelligent agents (presents multiple choice options, continues scenario)	Giselle can experience how it feels like to react to difficult teaching situations Giselle can experience how the consequences of her decisions feel like
Reflective observation	Interaction with other users (discussion with other students)	Giselle can discuss her feelings during the experience with other students and reflect about her emotional response during the scenario
Abstract conceptualization	Interaction with other users (discussion with other students)	Giselle can discuss her reactions to difficult teaching situations with other students to develop theoretical ideas on how she could improve her teaching style
Active experimentation	Realistic scenario (different teaching situations) Interaction with intelligent agents (presents multiple choice options, continues scenario)	Giselle can try different multiple choice options to see how this changes the outcome of the scenario

5. Focus group results

5.1. VR business pitch

Overall, most participants of focus group A evaluated VR Business Pitch as useful because *"the application would allow to practice presentation skills before they have to be applied in a serious situation"* (A5).[1] A student emphasized that the application would be helpful because students are required to give presentations in class although *"presentation skills are something you do not get taught at university"* (A2). Another student imagined that it would be helpful for nervous students because *"you just feel more secure when you have done something like this business pitch before"* (A7). Two participants perceived that presentation situations occur rarely in the business administration program which is why they would not use the application often (A1, A3). One of these students explained that the application would provide more value if it could also be used to memorize learning content for the exams (A3). Two other students liked the idea of VR Business Pitch but imagined that the direct feedback via the virtual manager's facial expressions would overwhelm them (A1, A6). Related to this, one student explained that it would be stressful if *"the virtual manager looks mad, but I do not know what I did wrong"* (A6).

The participants of focus group A improved the prototype so that it addresses Pascal's needs better and suggested that the application should allow him to upload and present lecture slides. Instead of summarizing lecture contents in a written form, he could summarize the lecture slides during his presentation. An intelligent agent in the audience could be connected to the Internet and automatically fact-check his presentation. This way, the application would not only allow him to improve presentation skills for the special occasion of a business pitch but also to learn for exams. To further increase the number of useful applications, the participants suggested to implement different types of presentation scenarios (e.g., job interview, presentation in class, small audience, large audience). One student also suggested to replace the intelligent agent with a real audience to increase the realism of the experience (A3). She imagined that other students could join the presentation session, ask questions, and give feedback at the end of the session. However, this suggestion was heavily discussed because for the other students the possibility to practice in a safe environment without a real audience would be the actual benefit of the proposed application.

[1] In the following, we refer with *Ab* to Table 2, p. 6, whereas $A \in \{A,B,C\}$ is the group and *b* is the participant number.

One participant explained: *"I would really have to be in an isolated room and be sure that nobody could enter during that time. If I knew that someone could listen or look at me while I was presenting, that would inhibit me enormously"* (A1).

5.2. VR tweet emergency team

VR Tweet Emergency Team was perceived as useful by all students in focus group B. Three students pointed out that the application would help to understand the relevance of their study program because very often they ask themselves in lectures: *"How can I use this theoretical concept in a future job? For which kind of job do I actually need this?"* (B2). They liked that the VR case study showed them a meaningful use case for social media analytics in the real world (B2, B4, B5). One student added that *"it would also be much more exciting than just learning the theory"* (B1). Another student agreed and could also imagine *"that you remember it longer than if you had learned it theoretically. It just stays in your head, because it's something different"* (B6). For one student, the usefulness of the application depended on the possibility to simulate the outcomes of different analysis approaches: *"Because I love learning with 'Okay, that didn't work, let me try something else.' If you could see at the end of the scenario how many people you saved with your analysis, I think that would be very cool"* (B4).

To afford reflective observation, the participants emphasized that the realistic scenario should end with feedback about the team performance and the consequences of their decisions (B2, B4). Furthermore, the participants highlighted the importance of animated and visual instructions explaining each analysis method to afford abstract conceptualization (B3, B4, B6). Otherwise, they focused on improvements to increase Marcel's learning motivation and awareness about his learning progress. The participants suggested virtual rewards (e.g., points, levels) for each successfully completed scenario allowing Marcel to compare himself with other students (B1, B2, B6). Moreover, the focus group participants imagined that Marcel could unlock more advanced analysis methods with each level (B3, B4). The collaborative aspect of the initial prototype raised discussions in the focus group because some participants preferred to practice analysis methods in an individual learning space first before engaging in a more complex group exercise (B3, B6). Therefore, the participants agreed on a distinction between an individual and a group learning space. In the individual learning space, all students could sit at their own workplace in the virtual emergency control room. However, they could raise their hand and other students could decide if they want to walk over and answer the question of their fellow student. If students feel prepared for a group exercise, they could enter the group learning space where all students could manipulate the tweets and social network graph together while discussing their joint decision.

5.3. VR classroom simulator

The participants of focus group C liked that VR Classroom Simulator would allow them to practice different teaching situations *"without the nervous feeling that you are really standing in front of people"* (C4). However, two students emphasized that they would only feel comfortable to practice teaching in VR if they could use the application at home or in a locked room (C3, C4). One participant found the initial prototype extremely useful *"because then you also notice whether the teaching profession is really something for you or not. Learning is one thing and putting it into practice is another thing"* (C2). The other participants agreed and also appreciated that the application would allow them to apply theoretical knowledge in practice. It was perceived as particularly useful that students could see the consequences of their decisions and develop theories on how to improve their teaching (C2). Only one participant was sceptical whether difficult teaching situations could be represented realistically enough in the virtual environment but still liked the idea (C3). All participants agreed that VR Classroom Simulator should not only allow Giselle to practice difficult teaching situations but also to give a complete lesson. This would enable Giselle to improve the declarative knowledge about her teaching subject and her presentation skills as well.

During the group discussion, the students improved the initial prototype's affordance for concrete experience. They suggested to exploit the full potential of VR by increasing the realism of the virtual environment and the interaction with the intelligent agent. For example, Giselle should be able to speak with the intelligent agent instead of having to select multiple choice options (C4). Furthermore, the application should not be based on 360° videos because the students' behavior would be the same every time. Instead, the participants imagined a realistic virtual classroom environment inhabited by intelligent agents whose behavior could be randomized to a certain degree (C1, C3, C4). To feel more like a real teacher, the participants proposed that Giselle should be able to write at a virtual chalkboard (C1, C3, C4). One participant suggested that haptic feedback would allow her to experience consequences from her decisions in a more realistic way (e.g., if an argument escalates and a student throws something at her) (C3). Furthermore, the participants imagined that the application enables her to walk over to individual students for a more private conversation (C2, C4). The focus group participants also thought about how to afford reflective observation for Giselle's fellow education science students. They suggested that other students could join her teaching sessions, learn by observing her behavior and give feedback at the end of the session (C1, C2, C4). For three participants, it was also important that the intelligent agent provides theoretical explanations for wrong decisions to afford the learning mode of abstract conceptualization (C1, C2, C4). Furthermore, the focus group participants suggested to implement a score system that enables Giselle to assess her learning performance and motivates her to improve in the next scenario (C1, C2, C4).

6. Discussion

The aim of this research was to examine how students and lecturers imagine the future of VR-based learning and how VR can afford experiential learning processes. We applied a user-centric design thinking approach and conducted three workshops which resulted in three innovative VR prototypes that address the needs of students: 1. VR Business Pitch, 2. VR Emergency Team, and 3. VR Classroom Simulator. Over the course of three focus group discussions, students evaluated the prototypes and refined these in a way that they better address *their needs* and afford all four experiential learning modes. As summarized in Table 8, the analysis of the prototypes resulted in nine VR design elements that are crucial to afford the four experiential learning modes, namely 1. concrete experience, 2. reflective observation, 3. abstract conceptualization, and 4. active experimentation. In the following, we will derive design principles based on our findings and discuss them in light of previous research. For each design principle, we state whether it primarily aims at designers of VR applications for higher education or the educators who use them (which is not mutually exclusive).

6.1. Principle of technical and pedagogical considerations: identify both the unique technical opportunities of VR and pedagogical requirements (designers and educators)

Previous researchers already emphasized that there should be an alignment between student needs, learning habits, learning tasks, learning processes, and technology affordances (Antonenko et al., 2017; Dalgarno & Lee, 2010; Fowler, 2015; Kirschner et al., 2004). Nevertheless, a recent systematic literature review of educational VR applications revealed that the development is often not explicitly grounded in learning theories (Radianti et al., 2020). Especially when it comes to emerging technologies such as VR, we argue that it is important to design with purpose. It might be compelling to ask: *"What can we do with this emerging technology?"* In our view, it is at least equally important to

Table 8
Summary of design elements providing experiential learning affordances.

	Experiential learning affordances			
Design elements	Concrete experience	Reflective observation	Abstract Conceptualization	Active Experimentation
Realistic surroundings	Virtual meeting room, emergency room, or classroom	–	–	–
Passive observation	–	Observing the sessions of other students	–	–
Character movement	Walking over to other students	–	–	–
Basic interaction with objects	Interaction with chalkboard, tweets, and social network	–	–	Interaction with tweets and social network
Interaction with other users	Group tasks; presenting in front of other students; voice chat	Feedback from other students; voice chat	Discussion with other students; voice chat	–
Interaction with intelligent agents	Realistic facial expressions; scenario manager; randomized behavior; voice input	Realistic facial expressions	Theoretical explanations for wrong decisions	Realistic facial expressions; scenario manager; randomized behavior; voice input
Instructions	–	–	Videos; animated explanations	–
Feedback	–	Feedback report; realistic facial expressions; feedback from other students	–	Feedback report; realistic facial expressions; feedback from other students
Realistic scenario	Different crisis, teaching, or presentation scenarios	Different endings based on performance	–	Different crisis, teaching, or presentation scenarios

ask: *What kind of learning outcome should be achieved and what is the most effective learning process to achieve this outcome?"* It then makes sense to evaluate whether the unique opportunities of VR enable this learning process in a better way than alternative delivery methods. In our study, we applied this design principle and identified VR design elements that could be implemented to afford a holistic experiential learning process. In the following, we will derive more specific design principles from our findings that address how the unique opportunities of VR can provide an added value for experiential learning.

6.2. Principle of knowledge contextualization: enable students to apply theoretical knowledge in realistic job scenarios (designers)

The design thinking workshops and focus groups revealed that students do not feel well prepared for their future job. Students reported that they often miss the connection between theoretical knowledge, particularly those they have to learn by heart, and the application of this knowledge in practice. This aligns with San Chee (2001) who argued that students often *"know about"* phenomena from textbooks but lack an *"understanding"* of how to apply their knowledge in practice. He advocated the use of VR for learning through direct experience and saw a lot of potential in simulation-based applications (San Chee, 2001). Other researchers also highlighted the contextualization of learning processes as a unique strength of VR (Aiello et al., 2012; Dalgarno & Lee, 2010). Although we conducted design thinking workshops with students and lecturers of different study programs, the three developed prototypes have one thing in common: They allow students to experience difficult situations in their future job (concrete experience) and experiment how to deal with them in the best possible way (active experimentation). The developed prototypes can be described as job simulators and aim to improve practical-procedural skills, analytical thinking, and collaboration skills. They thereby also bring together theory and practical application closer in time, which could bolster the learning success. A previous literature review of VR applications in higher education revealed that most applications prioritize procedural-practical skills over declarative knowledge (Radianti et al., 2020), but most apps discussed in the literature are still in the research stage. Therefore, most of them are not yet available in VR app stores. In contrast, a recent study on VR app markets found that the majority of accessible apps on the market aim to improve declarative knowledge rather than procedural-practical skills (Radianti, Majchrzak, Fromm, Stieglitz, & Vom Brocke, 2021). This highlights a gap between student needs, research and available VR apps on the market. Further research should uncover best practices on how to implement the VR-based application of theory to real-world problems.

6.3. Principle of realism and interactivity: provide a realistic and interactive virtual environment to afford concrete experience and active experimentation (designers)

To afford concrete experience and active experimentation, the participants suggested realistic surroundings and interactive scenarios as key design elements. This finding aligns with Radianti et al. (2020) who identified realistic surroundings and basic interaction with objects as most frequently used design elements in VR applications for higher education. Likewise, Chavez and Bayona (2018) identified interactive capability and immersion interfaces as the most important characteristics of VR in education. Kwon (2019) proposed that enhanced vividness and interactivity in virtual environments improve the learning effectiveness as students perceive the learning experience as closer to reality. In our study, we identified three aspects that contribute to a realistic experience: 1. appearance, 2. interactivity, and 3. behavior. The participants preferred a highly realistic appearance of avatars including gestures and facial expressions although they anticipated current technical limitations. With regard to the environment, realism rather meant that the environment should be clearly recognizable as such. For example, a virtual classroom environment should include a chalkboard and books because these objects make a classroom what it is. This aligns with Bricken (1990) who argued that our flexible minds allow us to interpret the simplest cartoon worlds. However, virtual objects should not only serve as decoration, but students would like to interact with them in expectable ways, aligning for example with real-world physics (such as, a student should be able to write with a chalk object). The participants perceived interactive objects as central to increase the realism of the experience but also to offer various opportunities for active experimentation in the virtual environment. For example, one prototype included a virtual phone that students could use to make their final decision in the scenario (increased realism). The participants suggested other objects such as an interactive social network graph to enable students to try different analysis approaches (active experimentation). Another aspect of realism that received less attention in previous research represents the behavior of non-human actors in VR applications. For example, Li et al. (2019) developed an educational VR application for children with autism spectrum disorders allowing them to play through interactive social stories and respond in socially appropriate ways by tapping rating buttons. Instead of multiple-choice options or sequential scripted interactions, the participants in our study imagined intelligent agents who are able to process speech of students and react in appropriate ways. These considerations not only put much focus on the work of the designers, but they also imply that increased VR usage in education would benefit from comprehensive frameworks that aid in the generation of apps.

6.4. Principle of integration: cycle between concrete experience and active experimentation activities in VR and reflective observation and abstract conceptualization activities in class (designers and educators)

In the design thinking workshops, the participants focused on developing affordances for concrete experience and active experimentation. In the focus group discussions, the participants tried to refine the prototypes in a way that they also afford reflective observation and abstract conceptualization. However, they had difficulties to imagine design elements that truly exploit the unique strengths of VR. For example, they suggested to afford abstract conceptualization by implementing pop-up windows with textual explanations. It might be possible to implement these in VR but they do not necessarily provide an added value. This aligns with Bell and Fogler (1997) who pointed out that "it would be a huge waste for VR to duplicate what students can learn from other media". In addition, Petersen et al. (2020) found that providing learning material before an educational VR experience improves knowledge transfer and reduces cognitive load. In the focus groups, some students expressed that they would not use the prototypes often because they might not be well suited to learn the declarative knowledge required for exams. Instead, the participants imagined using VR *in addition* to their lectures to better understand how their future job could look like and how their theoretical knowledge might become relevant in their future work life. This supports the findings of Jarmon et al. (2009) who found that students engage in concrete experience and active experimentation in Second Life while reflective observation and abstract conceptualization rather took place outside of the virtual environment. Particularly for educators this principle implies *"thinking out of the box"* instead of expecting that merely virtualizing existing content would provide added value.

6.5. Principle of psychological comfort: provide students with the opportunity to practice skills in private spaces before allowing other students to join their learning space (designers and educators)

Previous studies typically address motion sickness as a physical discomfort factor when using VR (Shin, 2017). However, our study draws attention to a psychological comfort factor that is related to the extent in which VR offers a safe and protected space for learning. This includes a private space in the real world but also an individual learning space in the virtual environment which enables learning with intelligent agents instead of real students. In the focus group discussions, many students expressed that they would feel uncomfortable to wear a VR headset in public. For example, they were concerned that other students could watch them while they practice presentation skills. As a solution, they suggested providing students with a headset at home or rented access to locked rooms at the university library. If we expect that students immerse in a virtual world, stimuli from out of this world might be perceived as intrusive – in a way like a person who immersed in a thrilling book would be very upset with suddenly being startled. Furthermore, we argue that it is important to consider the learning habits of students. In our study, many students reported that they usually summarize lecture slides and learn them by heart before they engage in learning groups to gain a deeper understanding of the content. As a result, the focus group participants heavily discussed whether they want to incorporate a peer assessment approach into the prototypes. Previous studies already incorporated a peer assessment approach into educational VR applications and found a positive effect on learning effectiveness, perceived self-efficacy, and critical thinking (Chang et al., 2020). Although the peer assessment approach might be effective, most participants in our study preferred learning with an intelligent agent first before allowing other students to evaluate their performance. As a result, many participants suggested offering students the possibility to switch between an individual and a group learning mode. This principle challenges designers and educators alike in providing non-linear, multiple options learning.

6.6. Principle of Gamification: embrace the gaming character of VR to increase learning motivation (designers)

Most participants associated VR with gaming and suggested the implementation of typical rewarding game elements (e.g., scores, levels, achievements). The participants did not associate these game elements with experiential learning affordances. However, they argued that game elements would make learning more fun and motivate them to use the application. In a previous study, Su and Cheng (2019) found that a gamified experiential learning approach also resulted in better learning outcomes. Likewise, Dalgarno and Lee (2010) highlighted the potential of 3D virtual learning environments to increase intrinsic motivation and engagement (Dalgarno & Lee, 2010). Therefore, we recommend designers to embrace the gaming character of VR also in serious contexts.

7. Conclusion

The goal of our research was to examine the potential of VR technology to afford a holistic experiential learning cycle. We approached this goal from a user-centered perspective, and thus conducted three design thinking workshops with interdisciplinary teams of students and lecturers. The workshops revealed that students demand a shift from traditional lectures to learning spaces that foster experiential learning. Together, students and lecturers developed three innovative VR prototypes to address real student needs and support an experiential learning process. These prototypes were evaluated and refined in three focus groups with students. Based on a qualitative analysis, we created a systematic mapping of VR design elements and experiential learning affordances. Thereby, we contribute a deeper understanding of how educational VR applications could be designed to afford each experiential learning mode: 1. concrete experience, 2. reflective observation, 3. abstract conceptualization, and 4. active experimentation. Furthermore, we extended the analysis framework for the identification of educational VR design elements by Radianti et al. (2020). We added the design element interaction with intelligent agents proposing that the combination of VR and artificial intelligence offers unique opportunities to afford a holistic experiential learning cycle.

These findings are also of significance for the scholarship of Internet-enabled higher education teaching and learning. Usually, experiential learning activities in higher education include real-world experiences such as field trips. Internet-based VR applications enable the transfer of such experiences into online courses. The Internet is of particular importance when collaborative activities are a fundamental part of the experience - as exemplified by the "VR Emergency Response Team" prototype. Furthermore, the Internet is relevant for the realistic implementation of intelligent agents as part of VR-based experiential learning applications. As suggested by the participants, intelligent agents could retrieve information from the Internet to verify the accuracy of student responses in experiential learning applications (as proposed, for example, in the "VR Business Pitch" prototype). Intelligent agents could also communicate with each other via the Internet to simulate social behavior in learning scenarios (e.g., realistic student behavior as in the "VR Classroom Simulator" prototype). Our results thus point to relevant areas for future research on Internet-enabled experiential learning in higher education.

Our research has some limitations, which need to be mentioned – and which are the foundation for future research. The workshop and focus group participants were *subject matter experts* but not necessarily *technology experts*. Therefore, their suggestions for educational VR applications might not reflect the technological possibilities and limitations in their entirety. However, we think that a lack of technological feasibility at the present time should not restrict our thinking about innovations in higher education but rather reveals new fields for future research (e.g., the design of intelligent agents in educational VR applications). Nevertheless, future research could integrate technology experts in user-centered design processes as they might have further ideas on how to exploit the unique possibilities of VR for experiential learning. Furthermore, we created the mapping of design elements and experiential learning affordances based on the participants' discussion of the developed low-fidelity prototypes. Future research could implement the proposed VR applications and evaluate in real courses to what extent these afford each experiential learning mode and their impact on learning outcomes. Furthermore, the development of flipped classroom concepts that integrate VR experiences at meaningful times in the curriculum could provide an added value.

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Appendix A. Appendix

The appendix compiles the coding guides for VR design elements (Table 9) and experiential learning affordances (Table 10).

Table 9
Coding guide for VR design elements.

Category label	Category definition	Anchor example	Coding Rule
Realistic surroundings	Students can learn in a virtual environment that looks as realistic as possible. This design element covers high-quality graphics, realistic avatars, and representational fidelity. The latter aspect means that the virtual environment should be clearly recognizable, for example, a virtual classroom should have chairs, tables, and a chalkboard.	"I wouldn't do that with cartoonish avatars, because it's no problem anymore to *make them look realistic* with deep fakes" (C3).	Applies when participants talk about the visual appearance of the virtual environment or other users.
Passive observation	Students can look around in the virtual environment but they have no interaction possibilities. For example, when students can join sessions and learn by observing other students.	"I think it's a good approach to have a *fixed position* and not 10,000 other functions that you can do instead" (B1).	Applies when students do not have any interaction possibilities.
Character movement	Students can move around in the virtual environment. For example, students can walk over to other students, teleport through the room, or switch to a multiplayer room by interacting with a door.	"I would find it really cool if you just click on a door where you can visualize that you are *changing rooms*" (B6).	Applies when students can change their position in the virtual environment.
Basic interaction with objects	Students can select, pick up, or manipulate virtual objects using their controllers or hand gestures. For example, students can select a door to switch rooms, pick up a phone to log in a decision, or write on a chalkboard to take notes.	"Maybe you can visualize which vehicles you send where. Kind of like if you had to *place little cars on a little map*. Or you *pick up a phone* and you say 'Send all emergency services there and there'" (B6).	Applies when students use their hands or controllers to do something with a virtual object. Does not apply when students use their voice to interact with other students, characters, or intelligent agents.
Interaction with other users	Students can talk to each other via chat or microphone. The design element also covers interaction with other students as part of group work or multiplayer scenarios.	"I think it would be cooler, if you can *call other people with your headset* and say 'Yes, can you help me?'" (B2).	Applies when students speak or work with other humans. Does not apply when students interact with objects or intelligent agents.
Interaction with intelligent agents	Students can interact with intelligent agents that have a visual representation. The intelligent agents are able to process the speech and body language of the students, analyze how well they perform a certain skill and show a realistic reaction. For example, if a student practices presentation skills in front of an intelligent agent, the agent reacts with changing facial expressions based on the student's performance (e.g. bored vs. excited expression).	"One could also implement an adaptive CEO. The *artificial intelligence* would then know, 'Oh, he seems to be able to present super well, so I'll switch to a bit more strict behavior'" (A2).	Applies when students can speak with an intelligent agent which is defined as follows: *"A computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives"* (Wooldridge, 2009). To be intelligent, an agent further has to be reactive, proactive and social (Wooldridge, 2009).
Instructions	Students can receive instructions on how to use the VR app and explanations regarding the learning content. A non-player character can talk to the students and provide them with instructions. The instructions can also be displayed as written text or videos.	"Maybe you could start with a *tutorial* from a character, who appears and explains what different techniques are available and then you have to apply the different possibilities in the game" (B3).	Applies when students receive explanations on how to do something. Does not apply when students receive feedback on how well they have done something (feedback).
Feedback	Students can receive feedback about their learning performance. Feedback can be provided in textual, visual or auditory form. Students can receive feedback during a learning session or afterward.	"Maybe some *feedback* on the screen? There could be a little avatar next to the screen that says *'well done'*" (B6).	Applies when students receive feedback about how well they have done something. Does not apply when students receive explanation on how to do something (instructions).
Realistic scenario	Students can select different scenarios to practice a specific skill. For example, presentation skills can be trained in a different presentation scenarios such as business pitches, job interviews, or conference talks.	"I also think there could be *different endings*. Especially with things like that, whether or not you saved a lot of people in the end, *based on the decision you made*" (B4).	Applies when participants specified scenes, characters, situations, sequences of events, and in some cases different endings. Does not apply when participants only discussed the visual appearance of the virtual environment or characters.

(*continued on next page*)

Table 9 (*continued*)

Category label	Category definition	Anchor example	Coding Rule
	The ending of the scenario depends on the performance or decisions of the students.		
Virtual rewards	Students can receive virtual rewards for completing learning tasks successfully. For example, they can gain levels, ranks, and scores. They can also be rewarded through unlocking new learning content or scenarios.	"I think the aspect of being able to level up is really cool, even with scores and stuff like that" (B6).	Applies when rewards are tied to the learning performance of students. Does not apply when students automatically unlock new content over time.

Table 10
Coding guide for experiential learning affordances.

Category label	Category definition	Anchor example	Coding rule
Concrete experience affordance	Applies to all text passages where participants described that a certain design element would enable them to experience how their future job would feel like	"I find it useful because it is a situation that is difficult to get into as a student. *Being invited to a pitch* to a CEO is not an everyday *experience*" (A5).	Applies when design elements allow students to experience their future work environment, their future job tasks, and the consequences of their work-related actions. Does not apply when design elements allow students to experiment with different task approaches (active experimentation).
Reflective observation affordance	Applies to all text passages where participants described that a certain design element would enable them to learn by observing others or reflect about their learning performance	"Maybe you could also get *feedback* during the presentation, like 'Watch your arms', so that you *realize that you are not presenting so well*" (A3).	Applies when design elements allow students to assess how well they did a certain learning task. Does not apply when design elements allow students to develop new theories on how they could improve their performance (abstract conceptualization).
Abstract conceptualization affordance	Applies to all text passages where participants described that a certain design element would enable them to develop new theories or approaches on how they could improve their learning performance	"Maybe there should be an *instructional video*, where you go into certain individual aspects. For example, if you have a shaky voice when you speak, there are different exercises. That really helps to *understand how you can improve your weaknesses*" (A4).	Applies when design elements allow students to develop new theories on how they could perform better during a learning task. Does not apply when design elements allow students to assess how well they performed (reflective observation) or try out their new theories in practice (active experimentation).
Active experimentation affordance	Applies to all text passages where participants described that a certain design element would enable them to try out different approaches and learn from the resulting outcome	"If you can test how different analyses lead to *different endings*, that would be cool. If you would let two groups use different approaches and afterwards so and so many lives have been saved. I love learning with *'Okay this didn't work, I'll try something else'*" (B4).	Applies when design elements allow students to try out new approaches in practice. Does not apply when design elements allow students to develop new approaches on how to perform better during a learning task (abstract conceptualization).

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Social Media Data in an Augmented Reality System for Situation Awareness Support in Emergency Control Rooms

Jennifer Fromm[1] · Kaan Eyilmez[1] · Melina Baßfeld[1] · Tim A. Majchrzak[2] · Stefan Stieglitz[1]

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Abstract
During crisis situations, emergency operators require fast information access to achieve situation awareness and make the best possible decisions. Augmented reality could be used to visualize the wealth of user-generated content available on social media and enable context-adaptive functions for emergency operators. Although emergency operators agree that social media analytics will be important for their future work, it poses a challenge to filter and visualize large amounts of social media data. We conducted a goal-directed task analysis to identify the situation awareness requirements of emergency operators. By collecting tweets during two storms in Germany we evaluated the usefulness of Twitter data for achieving situation awareness and conducted interviews with emergency operators to derive filter strategies for social media data. We synthesized the results by discussing how the unique interface of augmented reality can be used to integrate social media data into emergency control rooms for situation awareness support.

Keywords Situation awareness · Emergency management · Emergency control rooms · Augmented reality · Social media analytics

1 Introduction

Crisis situations involve a high degree of uncertainty and the need for rapid, critical and potentially irreversible decisions (Rosenthal and Hart 1991). Emergency control rooms are facilities used during crisis situations to coordinate response and recovery actions, conduct strategic decision-making and manage resource allocation (Mignone and Davidson 2003). Among other sources, emergency operators obtain information through the calls they receive from citizens and decide about the resources required to support first responders at the scene (Militello et al. 2007). To make the best possible decisions about the allocation of resources, it is crucial for emergency operators to achieve a high level of *situation awareness* (Endsley and Garland 2000). This means they need to process sufficient information to develop an understanding of the present situation and project the future state of the situation (Endsley 1996). Especially in the beginning of a crisis situation, there is often a lack of information and emergency operators wish for access to further credible data sources (Tapia et al. 2013).

The adoption of smartphones equipped with multiple sensors and a constant Internet connection has increased the creation of incident reports in crisis situations and the volume of available information. In particular, social media posts from eyewitnesses are seen as a potentially valuable data source for emergency operators (Palen and Vieweg 2008; Palen et al. 2009; Sutton et al. 2008). Still, control rooms are hesitating to make use of *social media analytics* as it is challenging to filter relevant and credible information (Landwehr and Carley 2014). Moreover, social media data are complex since they are generated in an informal way, include many different data formats (such as text, video, audio) and are generated by unknown and diverse users and organizations (Stieglitz et al. 2018b). Due to the large amount of data available on social media, control rooms need filtering algorithms to categorize the data and visualize them in a meaningful way (Ludwig et al. 2015a; Stieglitz et al. 2018e). In addition, the integration of social media data into the information systems currently used in control rooms poses a further challenge that needs to be addressed.

Information systems for emergency management must be designed to reduce the operator's workload and support the

✉ Tim A. Majchrzak
timam@uia.no

[1] University of Duisburg-Essen, Duisburg, Germany

[2] University of Agder, Kristiansand, Norway

decision-making process in the dynamic work environment (Buck et al. 2006; Carver and Turoff 2007; Taylor 2004). The following quote illustrates the importance of information systems in this work environment: *"A crisis management plan is only as good as the information system that supports it"* (Housel et al. 2006). Over the years, the used systems have improved significantly through the lessons learned from retrospective analyses of real-world disasters (Perry 2003). However, crisis situations are also changing as they are not only becoming more complex in nature (Rosenthal et al. 2001) but their number is also *"increasing in proportion to the growing complexity of the world"* (Feng and Lee 2010). Therefore, it is important to constantly improve the used information systems to keep up with these new developments. *Augmented reality* is a technology that made major progress in the last decade and is now implemented in the industry (Palmarini et al. 2018). Recent results revealed that this technology can help operators to work faster and reduce their mental workload, for example, in procedural work where a fixed sequence of activities are carried out to achieve a specific result which is common for installation, assembly, and maintenance work (Braly et al. 2019). This reduction can lead to an increased situation awareness and in turn to better decision-making (Endsley et al. 2003). It still needs to be investigated to what extent these findings also apply for the operators working in emergency control rooms.

The goal of our research is to propose a conceptual augmented reality design for improving the situation awareness of emergency operators. First, we used the technique of goal-directed task analysis to analyze the situation awareness requirements of emergency operators. Second, we collected Twitter data during two heavy storms in Germany to discuss the usefulness of different types of tweets with emergency operators. Based on the results, we derived filter strategies that allow to identify the tweets that are perceived as most useful by emergency operators in crisis situations. Third, we applied the eight design principles for situation awareness (Endsley et al. 2003) to propose a conceptual augmented reality design for integrating the filtered Twitter data into the information systems of control rooms. Hence, we answer the following research questions with our study:

RQ1: What are the situation awareness requirements for operators working in emergency control rooms?
RQ2: Which types of Twitter data do emergency operators perceive as useful for achieving situation awareness?
RQ3: How can augmented reality be used to visualize the types of Twitter data which are perceived as useful by emergency operators for achieving situation awareness?

The remainder of this article is structured as follows: In the next section, we provide the theoretical background on situation awareness. Subsequently, we summarize previous studies on social media analytics and augmented reality in emergency management. Then, we describe our two-step research approach consisting of a goal-directed task analysis and expert interviews. Afterwards, we present our findings and answer our research questions by discussing the identified situation awareness requirements, derived filter strategies, and conceptual augmented reality design for integrating Twitter data into control rooms and improving situation awareness of emergency operators. We conclude with a summary of our contribution, limitations, and suggestions for future research.

1.1 Research Background

1.1.1 Situation Awareness

The formal definition of situation awareness is *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* (Endsley and Connors 2008). This awareness usually focuses on the information needed for a specific task or goal and is therefore critical for effective decision-making (Endsley et al. 2003). Typically, the concept of situation awareness is applied to operational tasks such as driving a car or flying a plane (Endsley and Garland 2000). Operators working in emergency control rooms require individual situation awareness, team situation awareness and shared situation awareness which emphasizes the need to achieve "a shared understanding of that subset of information that is necessary for each of their goals" (Endsley et al. 2003). Based on the formal definition, situation awareness comprises of three different levels: 1. *Perception of the elements in the environment*, 2. *Comprehension of the current situation*, and 3. *Projection of the future status* (Valecha 2019). The first step towards achieving situation awareness solely represents the receipt of information in its raw form and does not comprise any interpretation of the data (Stanton et al. 2001). The second step towards achieving situation awareness is to understand what the perceived data means in relation to the goal and objectives (Endsley et al. 2003). This comprehension is based on schemata or knowledge structures that are stored in the long-term memory and are activated by recognized patterns in the perceived elements (Sarter and Woods 1991). The third level of situation awareness describes the ability to predict how perceived elements in the environment will impact the future (Stanton et al. 2001). This allows operators to proactively avoid undesired situations and respond faster which is why a lot of experts in different work environments devote a significant amount of their time to form this ability (Endsley et al. 2003). In combination, the three levels of situation awareness help to make well-founded decisions which will affect the current situation.

The operator's decision-making performance will change the state of the environment, resulting in new elements the operator can perceive, comprehend, and use to predict future events. Figure 1 shows additional factors that have an impact on the achievement of situation awareness.

The operator's expertise helps to develop mental models and schemata allowing the comprehension and projection of the future faster and with less effort (Salvendy 2012). This can lead to a level of automation in mental processing that can create a positive effect on situation awareness since it reduces the mental workload of the operator (Endsley et al. 2003). Furthermore, the operator may have preconceptions of what he or she should see or hear in a particular situation because of prior experiences, mental models, and instructions (Endsley and Garland 2000). The capability and user interface of an information system also influence the achievement of situation awareness. The presented information and provided functionalities can be beneficial for obtaining situation awareness. However, especially with many elements presented simultaneously, it is important to support the perception of the most important elements (Endsley et al. 2003). Additionally, the goals of the operator are essential to the development of situation awareness as for many operators their individual goals determine the elements of the environment that are perceived (Endsley et al. 2003). This active approach of perceiving elements is also known as *goal-driven information processing* (Casson 1983). Conversely, data-driven processing of data describes when elements are perceived unintentionally and independent of the operator's goal (Endsley et al. 2003). Alternating between these two forms of processing is one of the most important mechanisms supporting situation awareness (Endsley et al. 2003). For instance, when an operator only focuses on a given goal and fails to consider cues that indicate that a new goal is more important, he or she might make bad decisions. At the same time, relying on data-driven processing is overly taxing and highly ineffective in an attempt to achieve a specific goal (Endsley and Garland 2000). Therefore, the right balance is essential for a good job performance. By understanding how an operator selects and uses goals, it is possible to design an information system that supports the perception of important elements in specific situations. Endsley et al. (2003) proposed eight design principles for creating interfaces that effectively support the achievement of situation awareness (Table 1).

1.1.2 Social Media Analytics in Emergency Management

The term social media describes *"a group of Internet-based applications that build on the ideological and technological foundations of Web 2.0 and that allow the creation and exchange of user-generated content"* (Kaplan and Haenlein 2010). Since everyone with a smartphone can share videos and pictures from the emergency scene, information can already be found on social media *before* authorities or

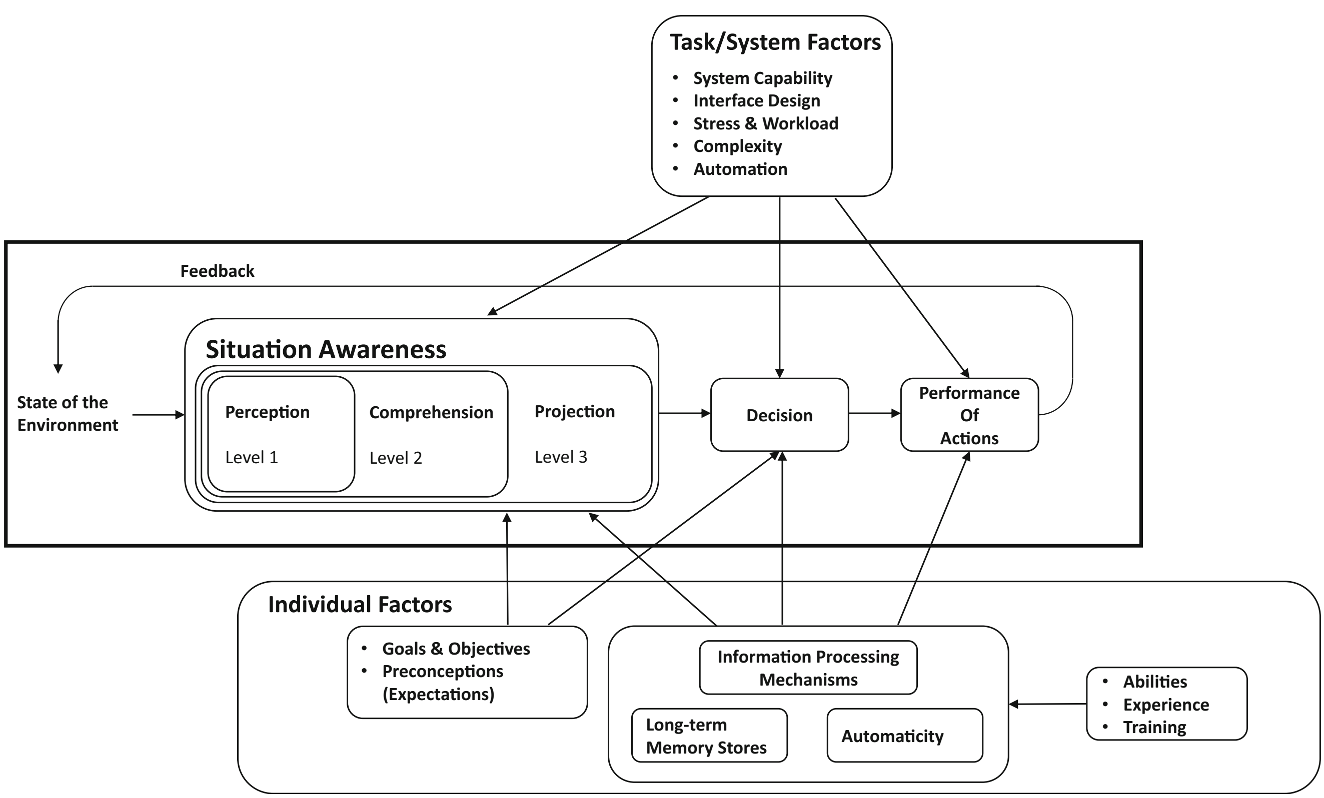

Fig. 1 Model of situation awareness in dynamic decision-making (adapted from Endsley et al. 2003)

Table 1 Design principles for situation awareness (Endsley et al. 2003)

Design principle	Description
Organize information around goals	All information that is necessary to make the major decisions related to a specific goal should be organized in close vicinity. Thus, information related to the same goal should e.g. not be spread across multiple displays.
Present level 2 information directly – support comprehension	Due to working memory limitations, it facilitates the work of operators to display level 2 information directly instead of level 1 information. The trustworthiness of tweets, for example, could be calculated by the system directly, so that operators do not have to use cognitive resources to evaluate the trustworthiness by themselves.
Provide assistance for level 3 situation awareness projections	As level three of situation awareness is hardest to achieve and requires well-developed mental models, an information system should support the projection of future states. For example, a trend display showing changes of a parameter over time allows the operator to predict future changes of this parameter.
Support global situation awareness	Information systems should provide a high-level overview of the situation and operator goals to achieve global situation awareness. Excessive menuing and windowing narrow the attention to a subset of the relevant information and should be avoided.
Support tradeoffs between goal-driven and data-driven processing	Goal-driven and data-driven processing (principle 1 vs. 4) should complement each other. Highly salient cues (e.g. flashing lights, loud sounds) direct attention away from goal-driven processing and should be reserved for the most critical events.
Make critical cues for schema activation salient	The activation of mental models and schemata are critical to achieve the highest level of situation awareness. Therefore, it is essential to identify cues that activate certain mental models or schemata and make these salient in the interface design.
Take advantage of parallel processing	The amount of visual information that can be processed by operators is limited. However, different modalities (e.g. visual, auditory, and tactile information) draw on different cognitive resources. An information system that supports these different modalities allows operators to process more information at once.
Use information filtering carefully	Computer-driven filtering reduces information overload but at the same time decreases global situation awareness because individual differences in situation awareness formation are neglected. Therefore, it is recommended to allow individual operators to determine which information they need to look at.

traditional media publish their reports (Cameron et al. 2012; Crooks et al. 2013; Huang et al. 2015; Mirbabaie and Zapatka 2017; Stieglitz et al. 2018d), sometimes even before emergency responders are on site (Stieglitz et al. 2018a). The wealth of user-generated content on social media could therefore serve as an additional information source for emergency operators to achieve situation awareness. Previous research has highlighted the usefulness of social media analytics before, during, and after a disaster (Ahmed 2011; Ghosh et al. 2018, Houston et al. 2015; X. Li et al. 2019). This applies especially to the micro-blogging service Twitter, which allows users to communicate in real time by allowing them to post public messages of up to 280 characters including images, videos, and links. There are example cases displaying the responsiveness of Twitter, e.g. in the 2011 Christchurch Earthquake in New Zealand, where *"the first tweet was within 30 s, the first photo was within 4 min"* (McLean 2015). Especially at the beginning of a crisis situation, emergency managers perceive a lack of reliable information (Tapia et al. 2013). Extracting posts from eyewitnesses could therefore provide actionable information for the planning of emergency operations (Landwehr and Carley 2014) and close information gaps concerning the situation at emergency scenes (Young et al. 2013) which accelerates the response time and reduces risks to citizens (Luna and Pennock 2018; Stieglitz et al. 2018c).

Although social media analytics could contribute to achieving situation awareness, emergency management organizations are still hesitant to adopt social media (Plotnick and Hiltz 2016; Stieglitz et al. 2018c). Nowadays, many emergency management organizations maintain a presence on social media to reach a larger percentage of the population in times of crisis (Eismann et al. 2016). However, analyzing social media data is still perceived rather as an experiment than as common practice (Imran et al. 2015; Lazreg et al. 2018; McLean 2015). Previous research identified the questionable veracity of social media information, the large volume of available data, the variety of data formats, and the high velocity of information diffusion as the most important technological challenges inhibiting the adoption of social media analytics in crisis management (Stieglitz et al. 2018c). Despite these challenges, many emergency managers acknowledge the potential benefits of social media data and believe that social media analytics will become an important part of their work routine in the future (Reuter et al. 2015). Regarding the questionable veracity of information, addressing the credibility of social media information is still seen as one main priority for the future development of social media analytics (Hiltz et al. 2020). Due to the unpredictable nature of crisis situations, emergency managers are used to limited and vague information, and therefore could trust social media sources, especially in the beginning of a crisis (Palen et al. 2011). However, it still poses a challenge to filter potentially useful information from the large number of irrelevant social media posts (McLean 2015). To address these challenges, Ludwig et al. (2015a) emphasize the need for filtering algorithms allowing to separate useful and credible information from the wealth of irrelevant social media content in a timely manner.

In previous research, crowdsourcing and automated approaches based on machine learning were identified as promising concepts (Imran et al. 2013; Tapia et al. 2013). Although crowdsourcing approaches can benefit emergency operations, they reach their limit as soon as the humans fueling them reach theirs. Therefore, automated approaches might be appropriate to solve the problem of analyzing the high number of social media posts in addition to crowdsourcing approaches (Hiltz and Plotnick 2013). However, it is difficult to correctly classify tweets using machine learning approaches because of the short text format (C. Li et al. 2012). Despite the advances that were made, it has been argued that the proposed solutions must become more accurate (Tapia et al. 2013). The examples in Table 2 demonstrate that the development of social media analytics applications for emergency management is already advanced and offering a variety of approaches with different strengths, while all of them express a demand for improvement and more accuracy. Especially, the processing time can be very long, because of the volume of data and the need of human input for labels (Troudi et al. 2018) and some authors argue that natural language processing needs to be improved (Aupetit and Imran 2017; Luchetti et al. 2017). Also, the automatic classifications could be more detailed and more robust, which implies the need for more detailed test labels (Alam et al. 2020; X. Li et al. 2019). Moreover, Lazreg et al. (2018) argue that social media analytics has to focus on providing information answering the specific needs of individual emergency managers.

1.1.3 Augmented Reality in Emergency Management

Recently, augmented reality has received attention in information systems research as the technology allows to present information in direct association with relevant elements in the physical world (Olshannikova et al. 2015). The unique interface of augmented reality is considered most useful when *"the success [of a task] is increased or made more likely (...) through additional visual information being presented alongside the physical world"* (Steffen et al. 2017). According to prior studies, the unique way of presenting information can improve the user's analytical reasoning and decision-making abilities (Chandler et al. 2015; ElSayed et al. 2016). Augmented reality systems are characterized through a combination of real and virtual content (Azuma 1997). This distinguishes them from virtual reality systems, which allow the user to immerse completely in a virtual world (Milgram and Kishino 1994). In the context of our study, we focus on the potential of augmented reality as it is critical for emergency operators to continuously perceive their real environment while processing information. This is due to the fact that, similar to the emergency response forces in the field, it is essential for operators in emergency control rooms to cooperate and achieve shared situational awareness for a successful emergency management (Seppänen et al. 2013). Augmented reality experiences are realized on different devices such as head-up displays, head-mounted displays, virtual retina displays, smart glasses, and hand-held devices (Van Krevelen and Poelman 2010). In previous studies, participants reported the heavy weight and the limited field of view as the major disadvantages of wearable devices (Braly et al. 2019). Moreover, the usage of augmented reality can lead to attention tunneling because the user's attention is drawn to highlighted objects (Dixon et al. 2013).

Nevertheless, there are already examples of augmented reality applications that have been used to support the development of situation awareness. For example, augmented reality systems have improved situation awareness when driving a vehicle (Park et al. 2015), riding a motorcycle (Jenkins and Young 2016), and driving automated cars (Lindemann et al. 2019). Similar results were also found in a study investigating the effects of wearable augmented reality on the operators of safety-critical systems. By providing real-time information through augmented reality, an improvement of the operator performance and situation awareness could be ascertained. These impacts are important because in a security-critical environment such as emergency management, they can prevent catastrophic loss of life or damage to property or the environment (Rowen et al. 2019). Additionally, Berkemeier et al. (2019) identified cross-industrial application areas and use cases for augmented reality systems based on the unique features of this technology. These identified application areas include communication, data visualization, text handling,

Table 2 Overview about state-of-the-art approaches for filtering social media data

Reference	Approach	Filter Criteria	Description
Ludwig et al. (2015b)	automated, crowdsourcing	search keywords, time period, retweets and up-to-datedness, mobile app requests	*CrowdMonitor:* Captures real movements via a mobile app and digital activities on social media to support situation awareness, crisis communication and integration of citizen volunteers in emergency management.
McLean (2015)	automated	eyewitness reports	Algorithm that could find 40 to 80% of eyewitness reports in a database, while being 80 to 90% accurate.
Basu et al. (2016)	automated, crowdsourcing	directly and actively asking for relevant information	Eyewitness reports are collected by asking the crowd about the disaster scene and automatically summarized to support situation awareness and decision making.
Luchetti et al. (2017)	automated	search keywords and hashtags, activity period, geographic boundaries	*Whistland:* An augmented reality solution consisting of a mobile app and an analytics dashboard that has multiple analysis views, tabular data and heatmaps.
Avvenuti et al. (2018)	automated	word embeddings, semantic annotators, collaborative knowledge-bases	*CrisMap:* A crisis mapping system based on damage detection and geoparsing, visualized in customizable, web-based dashboards. Capable of quickly analyzing textual social media data and producing crisis maps.
Bossu et al. (2018)	crowdsourcing	asking for reports on the severity of an earthquake	*LastQuake:* Intended for earthquakes can process information from websites, a Twitter quakebot, and a smartphone app.
Troudi et al. (2018)	automated	basic dimensions (topic, time, location)	Collects big data from various social media platforms as a mashup to detect disaster events.
X. Li et al. (2019)	automated	depictions of disaster damage	Identifying disaster images by differentiating between damage and no-damage depictions.
Zahra et al. (2020)	automated, crowdsourcing	domain-expert features combined with textual features	Identifying and classifying eyewitness messages in direct, indirect and vulnerable eyewitnesses using signal expressions.

and navigation which are also relevant for the work in emergency control rooms. Augmented reality could be beneficial in these areas by processing data to enable context-adaptive functions and information to enhance the operator's workflow (Berkemeier et al. 2019). Further examples of augmented reality use in the field of emergency management can be found in the literature: For instance, the multi-agent system called Smart Augmented Field of Emergency combines augmented reality, wearable computing, and intelligent agents to support teams in emergency and rescue scenarios (Brunetti et al. 2015). Furthermore, the augmented reality application THEMIS-AR was developed to assist first responders in disaster relief operations (Nunes et al. 2019). The application was designed to gather information, offer advice and guidance on response priorities, and provide situation awareness information based on georeferenced pictures that could be shared among different users. In addition, Brandao and Pinho (2017) made suggestions on how augmented reality could be used to improve the situation awareness of dismounted operators who tend to deal with a large amount of volatile information. Luchetti et al. (2017) describe the advantages of applying augmented reality on the emergency scene with their tool *Whistland* as *"making the information from social and sensor networks accessible for quick interpretation of geo-data to professionals and common users working on the scene of an emergency"*. Hereby, Luchetti et al. (2017) highlight the capability of augmented reality to simplify visualization and improve situation awareness. In the case of *Whistland*, the focus lies on mobile applications for the emergency field operators. In summary, most studies so far focused on augmented reality to improve situation awareness in other contexts than emergency management or on supporting emergency response teams in the field. However, it still constitutes a research gap to examine how augmented reality can be used to increase situation awareness and decision-making in the control room work environment.

1.2 Research Approach

1.2.1 Expert Interviews and Goal-Directed Task Analysis

The goal-directed task analysis is a cognitive task analysis technique that allows to identify critical decisions and information requirements of operators in various application domains (Endsley 1993). This method focuses on the basic goals of the operator, major decisions that need to be made to accomplish these goals and the situation awareness requirements that are mandatory for decision-making (D. G. Jones et al. 2012). This method is suitable for exploring what operators ideally want to know, regardless of whether this information is already available (Endsley et al. 2003). The knowledge of the required information helps designers to find better ways for the presentation of situation awareness information which leads to an improved decision-making performance of operators (Paulusová and Paulus 2018). To obtain this knowledge, interviews should be conducted with subject matter experts who have extensive knowledge of the operator's job (Rummukainen et al. 2015). The results are organized into hierarchical charts depicting the overall operator goal, the major goals, the sub goals, the decisions that need to be made for each sub goal, and the situation awareness requirements for each decision (Usher and Kaber 2000). The hierarchical chart aids in identifying the essential information that has to be provided by an information system to support the operator's situation awareness.

Goals are higher-order objectives necessary for a successful job performance and have to be distinguished from tasks or information requirements. Every major goal and subgoal is numbered to define the branch in which it is located; however, the numbers do neither indicate the sequence nor priority of goals. In some cases, a sub goal may be relevant for more than one major goal. In these cases, the sub goal can be described in depth at one part of the hierarchical chart and referenced at another part of the hierarchical chart using callouts. Each major goal forms an individual branch in the hierarchical chart with its own sub goals, decisions and situation requirements. Decisions are presented as octagons and phrased as questions that have to be answered. The subsequent level in the individual major goal branch includes the situation awareness requirements which are presented as rectangles and describe the information needed to answer the questions. The situation awareness requirements can be listed in an intended stacked format according to the level of situation awareness they belong to. This ensures that all situation awareness levels are considered when designing an information system for the operator's goals.

As part of the goal-directed task analysis, we conducted expert interviews with nine emergency operators working at fire departments throughout Germany (see Table 3), as these are the main responsible institutions in disaster control and civil protection activities (BBK 2020). The interviewees were selected due to their job experience to ensure that they were familiar with the goals, decisions, and situation awareness requirements in the control room work environment. Additionally, we selected operators with different roles in the operation center to consider different perspectives, and thus improve the depth of information obtained.

At the beginning, the participants were informed about the goal of the interview and their rights as participants. The interviewees gave their written consent to the recording of the interviews. In the first part of the interview, we asked the participants to introduce themselves and to talk about their tasks, job experience and position at the emergency operation center. We then explained the goal-directed task analysis technique to the interviewees and presented them a template for creating the primary goal hierarchy. In the second part of the interview, we asked the operators about the relevant goals to achieve a successful job performance and to describe their working steps in a typical emergency case chronologically. Afterwards, we presented a template for describing a major goal in detail to the participants. In the third part of the interview, we aimed to identify the decisions and situation awareness requirements related to the mentioned goals by repeatedly asking the following questions suggested by Endsley et al. (2003): *What decisions do you have to make to achieve this goal? What do you need to know to make that decision? Which information are needed to make that decision? How do you use that information? What would you ideally like to know? How do people do this badly? What do they typically fail to consider?* An overview about the structure and main questions asked in the expert interviews can be found in Table 4.

Table 3 Overview of respondents: first round of interviews

No.	Gender	Job Title	Experience
P01	male	Control Room Group Manager	16 years
P02	male	Control Room Group Manager	3 years
P03	male	Dispatcher	9 years
P04	male	Situation Service Leader	12 years
P05	male	Control Room Shift Supervisor	22 years
P06	male	Dispatcher	17 years
P07	female	Dispatcher	1 year
P08	male	Operations Manager	15 years
P09	male	Operations Manager	7 years

After each interview, we created a transcript following the rules of Kuckartz et al. (2008) and used the provided information to create a preliminary version of the hierarchical chart. We subsequently discussed this chart with the interviewees. This way, they could add, remove or edit certain aspects of the hierarchical chart and therefore improve the results. This procedure is also recommended by (Endsley et al. 2003) since it allows a review of the goals, decisions and situation awareness requirements by another person who is familiar with the illustrated steps. We conducted interviews until we reached theoretical saturation, meaning that the last interview did not result in any changes to the hierarchical chart. In the last part of the interview, we asked the participants how satisfied they were with the information systems currently used in control rooms, how well these meet the needs of the operators, and how these could be improved. Overall, the conducted interviews took between 30 min and one hour.

Table 4 Structure and main questions of the first round of expert interviews

Part	Main questions
Introduction	Sociodemographic data (age, job title, professional experience, personal tasks)
	Information about the emergency control room (responsibilities, tasks, structure, equipment, types of crisis situations)
Major Goals, Sub Goals, and Work Steps	Description of work steps during a typical emergency
	• What are the first questions you ask in an emergency call?
	• How do you process the information received during an emergency call?
	• How do you inform the first responders?
	• How and when do you inform other authorities that are needed at the emergency location?
	- Identification of major goals and sub goals
	• What are the goals of an emergency operator?
	• When you look at the goal hierarchy template, which of these goals would you classify as major goals and sub goals?
Decisions and Situation Awareness Requirements for Each Major Goal	The questions suggested by Endsley et al. (2003) were repeated for each major goal:
	• What decisions to you have to make to achieve this goal?
	• What do you need to know to make that decision?
	• Which information are needed to make that decision?
	• How do you use that information?
	• What would you ideally like to know?
	• How do people do this badly?
	• What do they typically fail to consider?

1.3 Twitter Data Analysis and Expert Interviews

To examine which situation awareness requirements could be fulfilled by integrating social media data into the information systems of control rooms, we first collected tweets during the storms *Dragi* and *Eberhard* in Germany and then conducted a second round of interviews with emergency operators about the usefulness of the collected data. Storm front *Dragi* was a less severe event on 09 March 2019 followed by the main storm front *Eberhard* that crossed the middle of Germany from west to east on 10 March 2019. In combination, these storm fronts resulted in the second highest warning level for storms in Germany and caused 10,000 operations for the fire department in the federal state of North Rhine-Westphalia (Waz 2019). The news reported on several property damages and impacted victims of the storm, namely 27 injured and one dead person in North Rhine-Westphalia. We collected the storm-related tweets on 10 March 2019 using a self-programmed java tool connected to the Twitter Search API. The search terms were German equivalents for the keywords *"storm"*, *"storm front"* and *"extreme weather"*, from which a tweet had to contain at least one to be included in the dataset. We decided against using the names of the storms as keywords, because they have an ambiguous meaning in German, and therefore many irrelevant tweets would have been collected. In total, the data set contained 13,155 tweets of which 6843 were retweets. The goal of the subsequent analysis was to identify the tweets from different category types that were rated most relevant by users and select these as examples for the interviews with the emergency operators. In a first step, we excluded all retweets, replies, and comments since these include duplicate information or are difficult to interpret without reading the related original tweet. By removing these types of postings, the data set was reduced to 6312 original tweets. In a second step, we excluded all original tweets with less than ten retweets since previous research has suggested that the retweet count can be used as an indicator for relevancy (Starbird et al. 2012). Finally, the data set contained 172 original tweets representing 1.31% of the total data set and 2.72% of the original tweets.

The remaining 172 original tweets were manually categorized by data format, role of the communicator, and type of content. Regarding the data format, we distinguished between tweets that consisted of 1) text only, 2) text and image, 3) text and video / GIF-file, 4) text and URL, and 5) mixed data formats (e.g. text, image, and URL). For categorizing the communicator's role, we combined the classification schemes from Stieglitz et al. (2017) and Olteanu et al. (2015) who identified the following communication roles during crisis situations: media organizations (e.g. news organizations, weather channels), governmental organizations (e.g. local or national administration, political parties, and public authorities), juristic persons (e.g. business organizations, non-governmental organizations), private persons (e.g. eyewitnesses, non-affected persons), and public persons (e.g. journalists, politicians, and celebrities). To categorize the type of content, we adopted the classification scheme from Heverin and Zach (2012) who distinguish between information, opinion, technology, emotion, and action tweets during crisis situations. Due to the large number of informative tweets in the dataset, we inductively generated subcategories for the category of information-related tweets (news, weather, traffic, and eyewitness reports). Once we completed the manual categorization, we selected the three most retweeted tweets for each category to present these to the interviewees as examples of realistic Twitter communication during a storm. An overview about the selected 21 example tweets can be found in Table 5.

We then conducted semi-structured expert interviews with five emergency management officers working at fire departments throughout Germany (see Table 6). All interviewees had experience with the work in control rooms and were involved in the emergency response to a storm event. To consider different perspectives about the usefulness of social media data, we have selected interview partners working at institutions with various implementation levels of social media. While the fire department of one interviewee was not using social media at all, the remaining fire departments used Twitter and Facebook for crisis communication and implemented a manual screening of tweets into their work routine.

At the beginning, the respondents were asked to introduce themselves and describe the typical work processes in a control room during a crisis situation. The interviewees also described the information sources currently used in their work. Afterwards, we asked the interviewees to describe how the fire department responded to the storms Dragi and Eberhard to get an overview about the timeline from the view of an emergency agency. Then, we presented the representative sample of tweets from our Twitter dataset to the interviewees and asked them to rate the usefulness of these tweets providing them with a scale from 1 (not useful at all) to 5 (very useful). During the main part of the interviews, we asked the respondents to explain the reasons for their evaluation in detail. Thereby, we frequently used follow-up questions to obtain more detailed information about the usefulness of the different data formats, communicator's roles, and content types. We ended the interviews with questions about the interviewees' intention to use social media as part of their work in the future. An overview about the structure and main questions asked in the expert interviews can be found in Table 7.

Table 5 Overview of the selected example tweets

Content category	Communicator's role	Data format	# Retweets
information	media organization (weather channel)	text and URL	128
(news)	media organization (news organization)	text and URL	40
	public person (journalist)	text and video/GIF-file	29
information	media organization (weather channel)	text and image	141
(weather)	media organization (weather channel)	text and image	116
	media organization (weather channel)	text and image	90
information	juristic person (business organization)	text only	159
(traffic)	media organization (news organization)	text only	99
	juristic person (business organization)	text and URL	68
information	public person (journalist)	text and image	54
(eyewitness report)	private person (eyewitness)	text and image	45
	private person (eyewitness)	text and video/GIF-file	39
opinion	public person (journalist)	text only	36
	public person (journalist)	text only	23
	public person (journalist)	text and image	10
emotion	governmental organization (political party)	text and image	65
	private person (eyewitness)	text only	29
	private person (eyewitness)	text only	16
action	private person (non-affected person)	text, image, and URL	458
	juristic person (registered association)	text and image	56
	media organization (news organization)	text only	53

Table 6 Overview of respondents: second round of interviews

No.	Job title	Professional experience		Current use of social media	
		Job experience	Storm experience	Crisis communication	Social Media analytics
P10	Head of the rescue control center	29 years	Kyrill (2007)	not implemented	not implemented
P11	Control center situation officer (press and public relations)	16 years	Eberhard (2019) Ela (2014)	Twitter Facebook	Manual screening TweetDeck
P12	Head of the office management staff (press and public relations)	9 years	Eberhard (2019)	Twitter	Manual screening
P13	Contact person (press and public relations)	27 years	Eberhard (2019) Friederike (2018)	Twitter Facebook	TweetDeck Hootsuite
P14	Officer (press and public relations)	35 years	Eberhard (2019) Ela (2014)	Twitter Facebook	Manual screening TweetDeck

Overall, the interviews lasted between 60 and 90 min. Again, the interviews were transcribed according to the rules of Kuckartz et al. (2008). We then analyzed the interviews using the approach of deductive category assignment according to Mayring (2014). The categories and subcategories used for the manual classification of tweets were selected as predefined categories for the qualitative content analysis of the interviews. From the transcripts, we extracted the

Table 7 Structure and main questions of the second round of expert interviews

Part	Main questions
Introduction	Sociodemographic data (age, job title, professional experience, personal tasks)
	Information about the emergency control room (responsibilities, tasks, structure, equipment, types of crisis situations)
Information Processing Procedures in Emergency Control Rooms	Personal experience and tasks during the storms Dragi and Eberhard
	Information processing procedures in emergency control rooms during natural disasters
	• What different types of data do you observe in your control center?
	• From which sources do you receive information?
	• How easy or difficult is it for you to find helpful information?
	• In which situations would you like more information?
	• Do you use social media use during disasters? If so, how do you use it?
Evaluation of Example Tweets	General opinion of social media use during crisis situations
	Evaluation of usefulness and trustworthiness of rated example tweets
	• Which data types do you think would be most useful in a crisis situation?
	• Information from whom would you trust?
	• From which roles do you find the available information most helpful?
Conclusion and Future Social Media Use	Future use of social media use
	• Could you imagine using social media in future crisis situations? If so, how?
	• We have already talked a lot about data formats and data sources. Are there any other aspects that might influence the usefulness of tweets?
	• What data would you ideally want to receive from Twitter?

opinions expressed about the usefulness of the selected tweets. By applying nominal category systems (Mayring 2014), we further distinguished between positive, negative, and ambiguous statements of the interviewees regarding the different categories of tweets.

2 Results

2.1 Situation Awareness Requirements

The goal-directed task analysis based on the first round of expert interviews resulted in a hierarchical chart consisting of the primary goal hierarchy and two individual branches including decisions and situation awareness requirements. All interviewees declared *"the saving of human and animal life as well as the protection of property and cultural assets"* as the overall operator goal in their profession. As illustrated in Fig. 2, the two major goals are divided into *"sending of emergency forces"* and *"support of emergency operations"*. The detailed individual branches of the first and second major goal can be found in the electronic supplementary material.

Major Goal 1: Sending of Emergency Forces The first major goal presents the process from receiving the call to sending the first responders. To determine the required emergency forces, the operator first has to identify the exact location (P09). Related to this, the second interviewee said: *"In the case of an emergency call, the first priority is to verify the place of operation. The reason for this is that if the conversation breaks off in between, then we have at least a place where we can send the emergency services*" (P02). The situation awareness requirements differ based on the location the operator tries to identify. For example, when the conversation indicates an emergency situation in a building, the operator tries to gain information about the street, apartment and building. However, when the caller describes a situation in a forest, this activates a different mental model and the operator's approach on the identification of the location changes. There is also the possibility that the callers on the phone do not know where they are or that they unintentionally give misdirecting information (P01, P06). These are situations in which the operator must use the described features in the caller's environment, such as bus stops or churches within sight. Another important situation awareness requirement regarding the location is the accessibility of the scene (P03). It is possible that a person is trapped in a car or in a building which requires additional rescue tools to be taken into account when selecting the emergency forces.

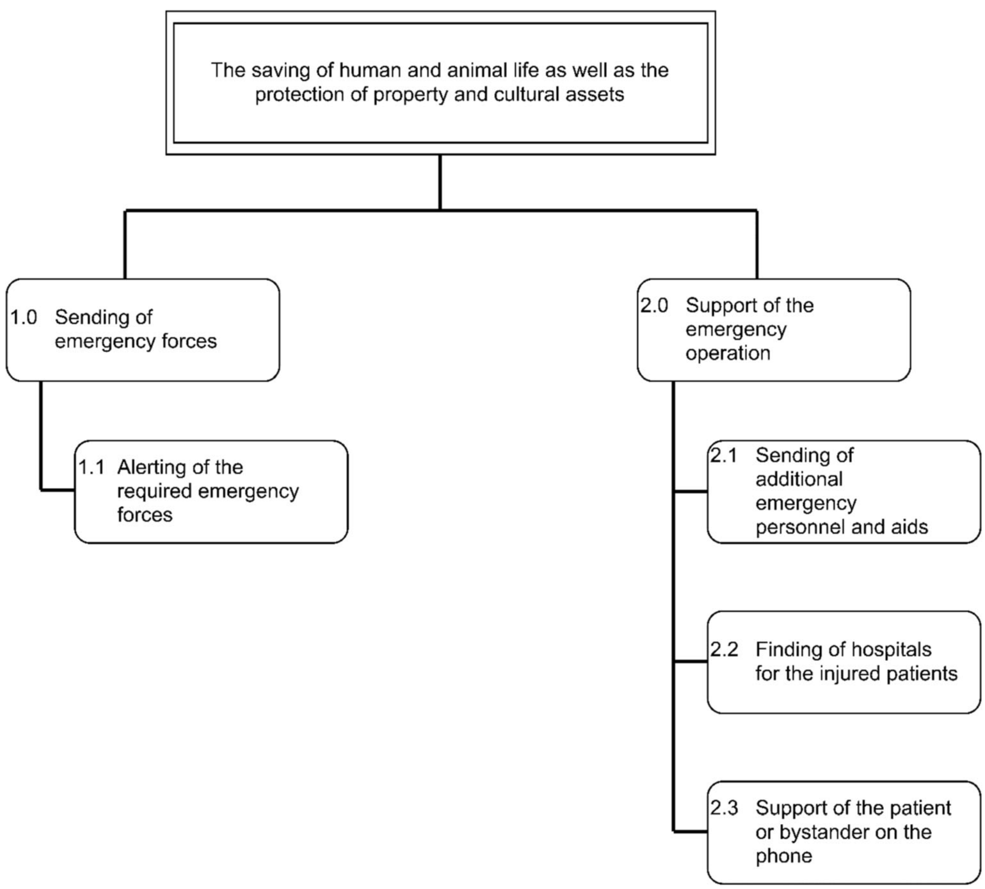

Fig. 2 Primary goal hierarchy

After gaining the required situation awareness information to identify the location and the accessibility, the operator needs to understand the situation to select the right forces. Similar to the information needed to determine the location, what the operator needs to know depends heavily on the nature of the emergency. For example, in case of fire the operators need information about the color of the smoke, the size and location of the fire, the surroundings, and the affected people to understand the current situation and predict the possible spreading of the fire (P01, P02). For an operation involving injured or sick people, the necessary information focuses more on the condition of the patient and the needed medical treatment (P03, P04). With the required information to locate the emergency, understand the situation and verify the responsibility, the operator is able to select a keyword according to which the system makes a suggestion regarding the needed emergency vehicles.

Furthermore, the operators need information to determine the necessity of additional special emergency forces. Operators often face situations where special tools or specially trained forces are required, for example, when a person is trapped or certain substances are needed to extinguish a fire. One interview partner said: "*Special means or special vehicles or forces are always required when the case is different than the norm. It already starts when we have a person in the water*" (P06). The same applies to the choice of additional authorities. If the operation involves situations the emergency forces are not trained for, the emergency operator may also involve other authorities trained for such situations. With all the above-mentioned situation awareness requirements, the operator can choose the emergency forces, special vehicles with the required tools, and authorities that are needed for the operation. The last step towards achieving the first major goal is to alert the selected emergency forces. However, this is an automated process and therefore no additional situation awareness requirements are needed.

Major Goal 2: Support of the Emergency Operation The second major goal involves the support of the emergency operation and includes three subgoals. The first subgoal is achieved by sending additional emergency forces and contains four decisions that require information similar to the decision of the initial selection of the required emergency forces. The main difference is that within the second major goal, the situation awareness requirements for these decisions are mostly obtained from the first responders and not from the callers (P04, P05). However, it is also possible that this information may be received from other callers, although this case occurs less often. The obtained information helps the operator to understand the lack of emergency forces as well as the mental condition of first responders and bystanders to forecast future demand. With this projection, additional forces, special vehicles, other authorities and psychosocial care can be sent after the arrival of the first responders at the scene of emergency.

The sending of further forces or aids is not the only way in which an operator can support an emergency operation. It often happens that these situations involve injured or ill people that need to be stationed in a hospital (P01). Since the first responders are busy with the handling of the accident, the operators are responsible of finding a suitable hospital. To achieve this, operators are dependent on the information they receive from the first responders since they decide if a person needs medical treatment. There are different situation awareness requirements to identify the adequate clinic. The most important one is the availability of the required equipment for appropriate medical treatment. For example, if a person has suffered a head injury in an accident, the hospital ought to have a neurological department. Additionally, the operator and first responders need to consider the preference of the patients. If they designate a clinic to which they wish to be transferred to and that clinic has the appropriate equipment, the emergency services will try to comply with the request. This preference may be based on factors such as proximity to home or family and experience or pre-treatment in the facility, which are also aspects that the operator considers even if the patient does not have a preferred clinic. The support of the operation is not only provided by assisting the emergency forces, but also by helping the person on the phone before the arrival of the forces. This help can include the instruction for medical treatment like cardiopulmonary resuscitation (P01). The situation awareness requirements to understand the need of this support on the phone is based on the operator's comprehension of the situation and the information gained in the conversation. It is possible that the callers request guidance because they do not know how to behave or that the operator understands that the caller is overwhelmed by the situation and predicts the need for an instruction.

2.2 Usefulness of Tweets for Situation Awareness Support

The interviewed fire fighters preferred to keep social media analytics separate from the working field of the emergency operators. One fire fighter stated that, *"it is not the task of the control center to access the Twitter channel"* (P11). In their daily social media work, the interviewees network and extend their range, e.g. by connecting and subscribing to official local channels, such as the police, press agencies, and traffic companies. During a crisis, the social media channels are operated alongside the normal press work and four interviewees already use social media to monitor ongoing crisis situations. If they find relevant information, they pass it on to the emergency management and the control room. Most interviewees saw a lot of potential in the automated analysis of large amounts of social media data and described the analysis of Twitter data as useful and inevitable while still mentioning some concerns regarding the trustworthiness. Regarding the *content* of a tweet, the interviewees generally preferred detailed, concrete and up-to-date information about the situation. They also mentioned the importance of hashtags, since they are monitoring manually and use the official hashtags, which they either registered or distributed themselves, to find relevant information. Credibility of the source was also very important to emergency managers and was perceived ambiguously by them. Concerning the different *communicator's roles*, official sources were viewed as trustworthy, e.g. transport services (Deutsche Bahn, the national railway operator) or governmental organizations (German Meteorological Service). In contrast, the interviewees were concerned with the credibility of private persons, while also stating that trustworthiness depended on the actual case and they take every hint seriously. Finally, most interview partners agreed, that the *data format* is not as important as the content itself. One person said: *"Whether it is a picture, a text or a video is irrelevant"* (P12). However, all interviewees rated the specification of an exact location as crucial for planning operations and sending task forces. Table 8 summarizes the types of tweets that were described as useful and trustworthy by the interviewees.

2.3 Conceptual Augmented Reality Design

The goal-directed task analysis is a technology-independent method that focuses on identifying the important goals, decisions, and situation awareness requirements of operators (D. G. Jones et al. 2012). A goal-directed task analysis can be used to determine what operators would ideally like to know to meet their goals, even if that information is not available with their currently used technology (Endsley et al. 2003). Therefore, the situation awareness requirements of the goal-directed task analysis can be used to explore possibilities of improving the presentation of information with any kind of technology (D. G. Jones et al. 2012). Based on previous literature, we identified augmented reality as a promising technology that might improve situation awareness in emergency control rooms (Brunetti et al. 2015; Luchetti et al. 2017; Nunes et al. 2019). In the following, we propose a conceptual augmented reality design considering the identified situation awareness requirements in the first round of expert interviews, the identified useful and trustworthy social media information identified in the second round of expert interviews, and the proposed situation awareness design principles from Endsley et al. (2003). We evaluated and improved the conceptual design based on the results of a workshop with two situation awareness and two augmented reality design experts.

Table 8 Usefulness for situation awareness and trustworthiness of the categories

Category combinations	Useful?	Trust-worthy?	Reasoning for evaluation
Traffic information from transport businesses	yes	yes	Provides situation information that simplifies the estimation of traveler movements and it not yet provided by another official information source *"As firefighters, we don't know what it looks like on the rails and it is important to know if trains are no longer running, and therefore many people may be waiting at stations"* (P12).
Eyewitness reports from private persons	yes	ambiguous	Interested in finding undiscovered places of action quickly, since an undiscovered operation could present a danger for civilians. However: concerns regarding the credibility *"If you can see that 10 people tweet from one place, because the dike threatens to break, then I have to look at it"* (P14).
Weather information from government organizations	ambiguous	yes	Redundancy with existing information *"We receive information for our city directly from the German Meteorological Service"* (P10).
News from media organizations and journalists	no	yes	Redundancy with existing information *"The official pictures of the Tagesschau and of the WDR are mostly pictures that they have from us, because we are on the scene"* (P14).
Weather information from media organizations	no	ambiguous	Redundancy with official statements from the meteorological center
Traffic information from media organizations	no	ambiguous	Redundancy with official statements from transport businesses
Emotion tweets	no	–	Not relevant for achieving situation awareness
Action tweets	no	–	Not relevant for achieving situation awareness *"Warnings from others are less relevant to us as we are already alerted and prepared"* (P12).
Opinion tweets	no	–	Not relevant for achieving situation awareness

Table 9 provides an overview about the participants of the workshop.

During the workshop, we demonstrated the design to the participants and asked them to discuss the following six questions: 1) How could the design enhance the situation awareness of an emergency operator? 2) How well does the design implement design principles that you are familiar with? 3) What are the innovative aspects of the design that distinguish it from other solutions in the literature or on the market? 4) What kind of technological challenges do you see in implementing this design? How could these challenges be solved? 5) What do you think is the added value of social media data for achieving situation awareness in control rooms? 6) What added value do you think augmented reality offers compared to the existing solutions in control rooms? In the following, we present our conceptual design and feedback from the situation awareness and augmented reality design experts.

The first design principle of *organizing information around goals* is already met by the currently used systems, as the control centers we visited used around 6–7 displays to present various software programs related to different goals. For example, there was one display that presented the information regarding the location of the emergency, one contained information gained from the emergency call, and another display was used to select the keyword and emergency vehicles (P01, P05). This division of visuals should also be implemented in augmented reality to fulfill the first design principle. However, augmented reality allows for more freedom when it comes to organizing information around goals: *"If you simply have to drag and drop the information with your hands, you can be a lot faster with grouping the information and categorizing it and get a nice overview"* (AR02). As the operators mentioned, the determination of the location is the most important situation awareness requirement to send the required emergency vehicles. Therefore, we are going to use the subgoal *"Identification of the Location"* as an example to show how an augmented reality interface could look like. The proposed interface includes a map and customizable filter options to display the types of tweets that were described as useful and trustworthy in the second round of interviews (see Fig. 3).

The map provides the operator with an overview of the area of the emergency scene including the different tweets depending on the type of crisis. The selection of the Twitter data that can support the operation could be accomplished by defining keywords for each type of crisis. The location could be derived by accessing the georeferencial data if provided by the user, the author location stated in the user profile, or by extracting mentioned locations from the tweet text. To differentiate the tweets from the marked place of the emergency, the tweets could be displayed as colored pins. The usage of customizable filter options is mandatory to assure that the operator using the system is not overwhelmed by the amount of crisis-related tweets. In our suggestion, the operator would be able to select different filter options by touching the document icon in the top right corner. By touching one of the pins representing a tweet, the operator could open a small window with a detailed view of the tweet. This view could contain information about the author and the tweet content. According to one of the situation awareness experts, *"the design also considers the principles of Shneiderman's information-seeking mantra very well by allowing operators to establish an overview first, then zoom and filter to get details on demand"* (SA02). Pictures and videos of the scene that were posted on social media were perceived as very useful by some subject matter experts and could increase the operator's situation awareness. One interviewee explained: *"Sometimes it is a matter of seconds. To have a system that picks up videos and pictures and shares them with the emergency services would be very useful for the first responders who does not know anything before coming to the scene"* (P07). The situation awareness experts confirmed the importance of pictures and videos because *"verbal communication can't always answer in a very good way what you as an emergency dispatcher want to know. For instance, if there is a fire. They want to know what the color of the smoke is. That is kind of hard for the caller to explain"* (SA02). The detailed view of the tweet could further include different indicators for the relevance of the content and trustworthiness of the author.

The second principle recommends the *direct presentation of the level 2 situation awareness requirements* to assist with the comprehension. To support the *"Identification of the location"*, our user interface includes a map of the affected area based on the entered address of the emergency with information about the surroundings. This map could contain further level 2 information about traffic jams, conditions of the streets, access to the location,

Table 9 Overview of workshop participants

No.	Gender	Job title	Research focus
SA01	female	PhD Student	Shared situation awareness, Additional experience: worked as an emergency operator for ten years
SA02	male	Post Doctoral Researcher	Social media and mobile apps for situation awareness
AR01	male	PhD Student	Multimodal augmented reality interaction design
AR02	female	Post Doctoral Researcher	Immersive technologies for skill development

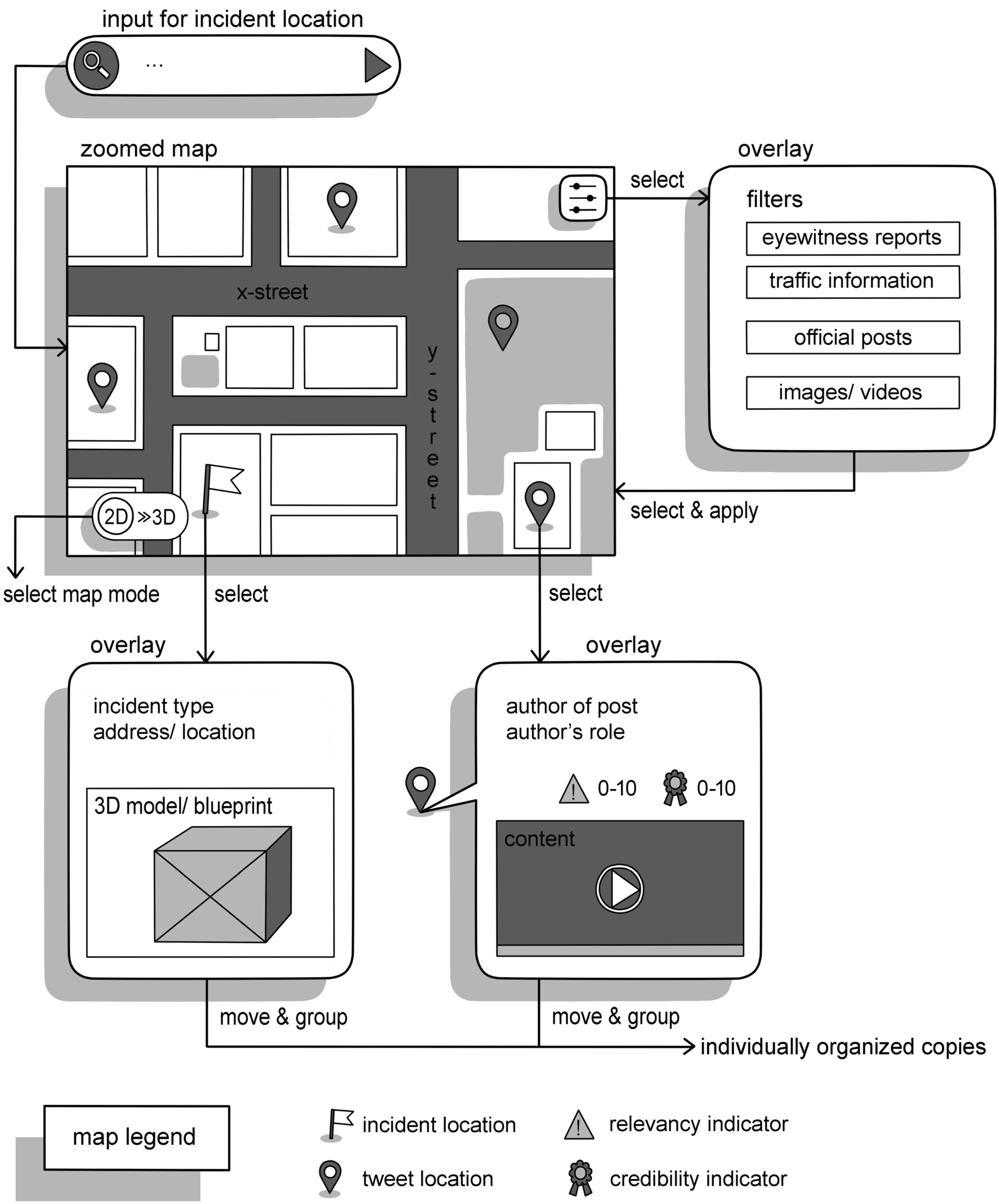

Fig. 3 Conceptual wireframe design for an augmented reality application in emergency control rooms

and the environment of the emergency. To increase their understanding of the situation the dispatchers already use Google Street View (P05, P06). The situation awareness experts also perceived that an additional 3D view of the map supports comprehension because, *"if you get some videos and you cannot fully comprehend from which angle or perspective it was taken, you* *can get additional insights if you have an additional 3D perspective"* (SA01). The other situation awareness expert added: *"I think the 3D perspective can sometimes be overwhelming, so two dimensions are good for the overview and three dimensions on demand when you need additional information"* (SA02). Especially the usage of 3D models was seen as useful. One emergency operator said: "*I personally already use Google [...] that is already a kind of 3D thing. [...] But it has to be easier. Google is not that easy, it cannot be done just like that and for us it has to be fast and secure and that is not the case on the Internet with such open software*" (P06). These 3D building models could present additional information regarding the accessibility of the scene or display the exact location like the floor where it burns in the case of a fire. For example, the windows of the room with the fire could be illustrated with the color red to make them salient while the entrance and emergency exits are presented in green. This way, the used colors also activate mental models and schemata of the emergency operators. However, this still represents a technical challenge as one of the augmented reality experts explained: *"If you want to have exact information perhaps where the emergency exits are, then you need some other data sources. Perhaps integrate data from the building or city departments"* (AR01).

The third principle suggests providing *assistance for level 3 situation awareness projections*. This can be achieved through displays that present changes in parameters over time. One of the augmented reality experts saw huge potential in using the 3D building models to display changes over time: *"For example, if some parts of the building broke down and you have pictures from social media. I think this could be really difficult but also an interesting challenge for future research. Maybe there is a way of getting into the perspective of where the social media photo was taken. And then use the photo to lay it over the 3D perspective you have"* (AR02). Currently, the control rooms use large monitors in the front of the room to display the changes of conditions in different areas (P01). For instance, one of these screens shows a weather map which presents possible storm incidents, climatic changes, and other variables. This representation of the weather parameters helps the dispatchers to recognize possible problems caused by storms at an early stage and prepare themselves accordingly. This representation already fulfills the third principle, however, augmented reality would allow the users to place this information as they like since the representation in the virtual environment does not depend on the physical equipment in the room. This possibility was also seen by one of the interview partners who said: "*We do not use such a thing [augmented reality]. But I think that would be a good thing, because we are building a situation wall, for example, for major damage situations, in which a map is presented that shows the burning objects and the units that are present in an emergency. [...] To present such a situation wall digitally with simple means would be a dream come true*" (P06).

The fourth design principle highlights that the *support of global situation awareness* is important. This can be achieved by giving the user an overview without restricting their access to support the selection of the highest priority goal. Augmented reality offers the opportunity to place a large number of virtual windows in a beneficial way, which ensures that the operators focus on the most important elements without creating an attention narrowing effect. In comparison to the currently used 6–7 monitors, augmented reality allows a larger overview which supports the global situation awareness. Therefore, excessive menuing and windowing with specific data in order to obtain information is not necessary. It is possible to provide the needed knowledge in different windows at the same time allowing the simultaneous perception without overloading the user with information. Therefore, the user interface should contain multiple elements, each providing the situation awareness information necessary for the respective decisions.

However, as described in the fifth principle, it is important to find a *balance between the goal-driven and data-driven processing*. An extreme tendency to one of the processing types is detrimental for the operator's attention and affects the situation awareness in a negative way (Endsley et al. 2003). The design in augmented reality should provide an overview over the important elements without overloading the user. Too few elements, on the other hand, can cause the user to have attention narrowing since not every important information can be perceived. The above-mentioned combination of elements already considers the fourth principle and thereby supports the data-driven processing. To enhance the goal-driven processing, an augmented reality system should make the high-priority elements conspicuous to the user, for example, by using different colors or a specific arrangement in the virtual environment.

According to the sixth design principle, it is important to make *critical cues for schema activation* salient. As mentioned before, mental models and schemata are important to achieve high level situation awareness. First of all, it is important to identify the cues that activate the mental models. For instance, control centers and hospitals use the traffic light colors along with the colors blue and black to prioritize injured patients of mass casualties (P03, P04). Green indicates the lightly injured, yellow marks the badly injured, and red the severely injured (P03). The additional color blue marks the patients who cannot be treated and black symbolizes casualties (P06). Since the red marked ones have to be treated faster, this prioritization helps the operators to organize the treatment accordingly (P03). These colors can be used as critical cues to activate specific mental models and schemata. For example, the previously mentioned relevance or trustworthiness indicators for the tweets could also define different colors for the pins on the map allowing the operator to react faster on the more important information.

Another way of supporting the operator's situation awareness is described with the seventh principle, which advises to *take advantage of parallel processing*. If it is possible, the system should provide not only visual, but also acoustic or haptic information. Since most information is gained through the emergency call, the auditory channel is already used in this work environment (P01, P02). To improve the situation awareness visually, the previously mentioned 3D building models could be utilized. Furthermore, one augmented reality expert highlighted the importance of a multimodal interaction approach: *"When you use gestures in the air, you don't have any feedback. This means the situation awareness could be reduced because the operators have to use mental capacities for just controlling the system"* (AR01). Therefore, we suggest enabling operators to switch between hand gesture and eye gaze interaction with visual feedback. The eighth design principle emphasizes the *careful use of information filtering*. The reduction of information is often times associated with the thought that it would lead to a reduction of information overload and an improved situation awareness. But this reduction is more likely to inhibit the situation awareness of the operator by removing important information (Endsley et al. 2003). The recommended approach is to give the user the opportunity to decide what kind of information he or she wants to see. One of the situation awareness experts suggested that the design could not only offer customized filter options for different types of tweets but also for different data sources: *"It could serve as a very good extensible base platform. When I was in contact with fire departments they were also concerned about drones. And you can extend your concept if you have some drones deployed and you click on a drone and see the live footage"* (SA02).

3 Discussion

3.1 Situation Awareness Requirements

The first round of expert interviews and the goal-directed task analysis were conducted to answer our first research question and allowed us to identify the goals, decisions and situation awareness requirements that need to be considered when designing a situation awareness support system for emergency operators. With this method, we were able to determine *"sending the emergency forces"* and *"supporting the emergency operation"* as two major goals that need to be accomplished to achieve the overall operator goal which is *"the saving of human and animal life as well as the protection of property and cultural assets"*. The different subgoals and decisions to achieve the first major goal focus on the operator's understanding of the situation and the selection of the appropriate emergency forces. To achieve the first major goal, the operator requires information about the location of an emergency, the accessibility of the emergency scene, information about what exactly happened at the scene, and information about the medical condition of affected people. We found that the *detailed description of the emergency location* constitutes the most important situation awareness requirement for emergency operators because this information enables them to send emergency forces even if all other relevant information is missing. It is especially critical that the emergency operators are mostly dependent on the information gained from the person who made the emergency call to make decisions about the sending of emergency forces. Thus, the integration of social media data into the control room work environment could be especially useful if the caller has only provided incomplete information. The second major goal focuses on sending additional emergency forces and aids to the scene, selecting an appropriate hospital for injured persons, and assisting callers with instructions on the phone. To achieve the second major goal, the operator requires information about the required number of emergency forces at the scene, the required knowledge, skills and authority to deal with extreme situations, the required special vehicles and tools, information about the mental condition of first responders and bystanders at the scene, information about the medical condition of affected persons, and information about the knowledge of the caller. The situation awareness requirements necessary to support the emergency operation are different from those required for the first major goal of sending emergency forces, since they are mostly obtained from the first responders at the scene.

These situation awareness requirements are essential to design a system that can support the operator's situation awareness. To obtain these requirements, we applied the goal-directed task analysis technique that was first demonstrated in the aviation domain and afterwards tested in different work environments, for example, in industrial plants (Paulusová and Paulus 2018) or within the army brigade (Bolstad et al. 2012). In the emergency field, there were similar approaches to identify the user requirements in emergency management such as the applied cognitive task analysis used by Pfaff (2015) or the hierarchical task analysis used by De Leoni et al. (2007). Compared to these approaches, our method resulted in a more detailed and comprehensive view of the required information to achieve a good job performance as an emergency operator. For example, the hierarchical task analysis utilized by De Leoni et al. (2007) revealed the different goals required to achieve the overall operator goal without describing the different decisions that need to be made. Since goals can involve multiple decisions to be achieved, it is important to also include them in addition with the required situation awareness information to completely understand the requirements in a specific work environment. The conducted expert interviews in combination with the goal-directed task analysis allowed us to illustrate the decision-making process of the emergency operators in a very detailed way. However, there are also studies that utilized the goal-directed task analysis in the emergency field. For example, the goal-directed task analysis was applied to identify situation awareness requirements during a single event like the attack on the World Trade Center (Dawes and Cresswell 2004). Thus, the obtained situation awareness requirements are not universally applicable like the results of our comprehensive analysis. Furthermore, Humphrey (2009) created a hierarchical chart using the goal-directed task analysis which included every stage and step involved in an emergency situation. The major goals in this study start with the prevention/deterrence of a crisis and end with the last steps of the recovery/remediation after a crisis situation. A similar broad view on the field of emergency management was also created by R. E. T. Jones et al. (2010) in which they additionally included major goals like the detection of bio events. Compared to our results, the decisions and goals are in some occasions akin but since we focused on the specific role of emergency operators, we were able to identify a considerable larger number of situation awareness requirements. In summary, our results represent a novel view with unprecedented detail of the situation awareness requirements of operators working in control rooms.

With the obtained situation awareness requirements it is possible to compare the information needed with the information available through social media. This allows us to determine how social media data can be used to further support the operator's situation awareness. For example, the geolocation of an eyewitness who posted a tweet about a certain crisis can provide useful information to achieve the subgoal *"Identification of the location"*. Since most users deactivate the sharing of their geolocation, this information could in many cases also be obtained through the post's content by using text and image analysis or integrating data from other social networks like YouTube or Facebook. For example, pictures or videos posted from the emergency scene could obtain information regarding the accessibility of the scene and details about the location which the operator did not receive during the initial emergency call. This information could further enhance the understanding of the situation which would make the decision-making easier. Information contained in the post could also support the operator in determining what exactly happened at the emergency scene. For example, user generated tweets from an emergency scene could be extracted by existing text mining tools and presented in an apprehensive way, so that emergency operators could estimate the threats of a situation, how many civilians are involved or how accessible the location is. Furthermore, traffic information posts from transport business organizations could provide information about where additional emergency forces might be needed. Similar to the location, the provided information can enhance the user's understanding of the situation, and thus the situation awareness. In combination with a time series variation analysis of the disaster damage, the relevant tweets will not only be useful during real-time operations but also to discuss a disaster mitigation plan.

3.2 Usefulness of Tweets for Situation Awareness Support

The second round of expert interviews was conducted to answer our second research question and allowed us to identify the types of tweets that emergency operators perceived as useful to achieve situation awareness. Our study confirms previous research results stating that emergency management organizations in Germany are still not incorporating the full potential of social media analytics (Eismann et al. 2016; Stieglitz et al. 2018c; Tapia et al. 2013). We found that *traffic information from transport business organizations* is perceived as particularly useful and trustworthy. One of the situation awareness experts explained: *"We have this road company and they have this official map where you could get this information from. But they are not too quick with putting in the information. It's not very implemented in their procedures I think. Maybe in some huge events, social media could be faster"* (SA01). In addition, the interviewees described *eyewitness reports* as useful but questioned the trustworthiness of private persons. Most tweets were rated as not useful, e.g. posts from Twitter profiles of media channels as well as emotional, action, and opinion tweets. However, in our view this represents an advantage for the integration of social media data into the work environment of emergency operators. If there is only a small number of tweets that is actually perceived as useful, filter algorithms can be used to exclude the large amount of irrelevant information. This way, the integration in of social media data into control rooms can provide an added value without causing information overload, which would negatively affect situation awareness. Consequently, filter strategies that specifically display traffic information and eyewitness reports are needed to improve the usefulness and increase the adoption of social media analytics solutions for emergency management. In previous research, it has already been proposed that *"a customization of filtering algorithms for the needs of emergency management agencies might be needed for them to respond to their specific crisis situations"* (Stieglitz et al. 2018c). Related to this, the eighth design principle for situation awareness demands the careful use of computer-driven filtering and recommends the use of customizable filter options (Endsley et al. 2003). Our research also revealed that individual operators have different perceptions of the usefulness and trustworthiness of different types of tweets. For example, some interview partners perceived weather information from media organizations as relevant while others considered them to be redundant. We therefore suggest to provide customizable filter options allowing emergency operators to adapt the visualization of social media data according to their needs.

The first step towards the development of filter strategies is improving the data collection process in existing algorithms by selecting only useful information for further processing and visualization. While there are already multiple approaches that focus on the extraction of eyewitness reports (e.g. Zahra et al. 2020), the development of algorithms to extract information from relevant business organizations such as railway traffic companies has been neglected so far. In this matter, our findings reveal that new crowdsourcing approaches or machine learning algorithms are needed. In a second step, the filtered set of relevant social media data needs to be visualized to support the situation awareness of emergency operators. As we identified the informativeness as the main attribute of useful posts, the visualization of social media data should be combined with a relevancy indicator that highlights the most important tweets. To assess the relevancy, the number of retweets can be considered, as previous research concluded that users mostly retweet posts that are either from official sources or from eyewitnesses (Starbird and Palen 2010). The interviewees also mentioned other aspects that could contribute to the relevance indicator: These include the @-function that marks messages directly addressed towards emergency management organizations, searching images in Google Pictures to ensure that they are up-to-date or have been used before, and the style of writing that can identify concrete and detailed information. The latter was used by Verma et al. (2011), who found that actionable tweets were objective and formal and could identify disaster relevant posts with this method. As not only relevancy but also trustworthiness is important to emergency operators, the relevant social media data should also be visualized in combination with a trustworthiness indicator, e.g. a traffic light system. Factors that could be integrated into such an indicator could be the verified badge that Twitter offers for accounts of public interest. Other criteria like the author's description and name, number of followers, formal language, and confirming the person's location could be applied for accounts without this label. Trustworthy networks could be organized through subscriptions to local officials and Twitter's list function, which can be used to incrementally organize private persons' accounts, whose trustworthiness might already have been proven in past events, into content groups (e.g. "local population") and monitor their tweets without subscribing to them. To the best of our knowledge, the combination of the previously named indicators for relevance and trustworthiness have not been implemented in previous research, although emergency managers often associate their willingness for the adoption of social media analytics with these two aspects (Zade et al. 2018). Most algorithms use informativeness as main criterion for data extraction and incorporate relevancy in their selection process. For instance, there are algorithms using the increase of attention and retweets to identify crisis-related tweets (Hiltz and Plotnick 2013; Starbird et al. 2012) and sorting their tweet list according to the number of retweets (Ludwig et al. 2015b). Other researchers rather focus on the trustworthiness of social media information (Lazreg et al. 2018; Tapia et al. 2013). Related to this, Hiltz et al. (2020) identified a rating of trustworthiness as one of 16 features that experts would find useful in software to support social media use in emergency management. Our proposed indicators can inform the implementation of this important feature.

3.3 Conceptual Design Augmented Reality Design

To answer our third research question, we synthesized the results and proposed a conceptual augmented reality design that integrates social media data into control rooms. The design includes a customizable filter function based on the previously presented filter strategies. Thus, the proposed design integrates only useful and trustworthy Twitter data so that situation awareness can be increased without creating information overload. At the same time, the design fulfills the eight design principles for situation awareness (Endsley et al. 2003) and addresses the situation awareness requirements of emergency operators we identified through the goal-directed task analysis. In previous research, there are already situation awareness support systems that integrate social media data and provide support for emergency responders; however, the needs of emergency operators have not been addressed so far. As a result, our proposed design can support situation awareness in a new field of emergency management. Furthermore, we emphasized a user-centered approach by conducting interviews with experts from the application domain to secure the usefulness of our design. There have also been other researchers who derived requirements for social media analytics from interviews with emergency managers (Hiltz et al. 2020; Stieglitz et al. 2018c) and the tool CrowdMonitor, for instance, was also developed based on expert opinions (Ludwig et al. 2015b). Nevertheless, the development of a design has not been combined with the goal directed task analysis, which ensures that our design fits the specific needs of emergency operators. Similarly to other approaches, e.g. CrowdMonitor, Senseplace2, Scatterblogs, Whistland or CrisMap, our design includes a map where emergency tweets can be located in a well-structured arrangement. However, we have deliberately avoided to include tweet lists or timelines in our design as it can be found in Whistland or Senseplace2, so that the emergency operators will not experience information overload. In addition, our conceptual design includes visualization using augmented reality technologies, which enable quick interpretation (Luchetti et al. 2017) and decision making through the unique presentation (Chandler et al. 2015; ElSayed et al. 2016). Regarding other implementations for augmented reality, mobile solutions like Smart Augmented Field of Emergency or THEMIS-AR have been designed to guide, inform and connect first responders, but they do not incorporate social media data, even though it was found to increase situation awareness. One of the augmented reality experts further highlighted how our proposed design extends previous research: *"Many augmented reality applications are just 2D screens with many layers. But what you mostly don't have is a bird eye view where you have a look at the scenery from top and can walk around and can enter different perspectives"* (AR01). With our design, we think outside the patterns of 2D screens and propose to implement a 3D view of the map on demand which could help the operators to interpret the perspectives of social media pictures and videos.

4 Conclusion

In the present study, we examined the potential of social media and augmented reality to enhance the situation awareness of emergency operators working in control rooms. In a first step, we conducted a goal-directed task analysis to identify situation awareness requirements of emergency operators. We were able to determine that information about the location constitutes the most important requirement for emergency operators to achieve situation awareness. In a second step, we collected Twitter data during two storms in Germany and conducted expert interviews with emergency operators to evaluate the perceived usefulness of Twitter data for achieving situation awareness. The interviews revealed that traffic information from transport business organizations and eyewitness reports from private persons were rated as most useful. In contrast, other types of informational tweets as well as emotion, opinion, and action tweets were either evaluated as not useful or trustworthy enough to be integrated into control rooms. In a third step, we synthesized our results by proposing filter strategies for social media data and a conceptual augmented reality design that illustrates how useful and trustworthy social media data could be integrated into control rooms. We evaluated and improved our design based on the results of a workshop with situation awareness and augmented reality experts.

With our research, we contribute a hierarchical overview about the goals, decisions, and situation awareness requirements of emergency operators that has not been presented in such a detailed form, yet. The identified requirements serve as an important foundation for the design of situation awareness support systems for control rooms in the future. We further shed light upon the potential of emerging technologies such as social media and augmented reality for emergency operators while previous studies mostly focused on other actors such as emergency response teams in the field. In addition, we propose criteria that can be used to develop filter algorithms for extracting eyewitness reports and traffic information from transport business organizations. So far, most studies either focused on extracting eyewitness reports or informational tweets from trustworthy sources. However, we found that many informational tweets from trustworthy sources were not perceived as useful by emergency operators, and thus we highlight the need for more targeted social media filter algorithms.

Our research has some limitations. First, the results might not be representative of the whole emergency management landscape due to the small sample size and restriction to emergency operators working in control rooms of German fire departments. To validate the results, future studies should examine whether different types of emergency agencies worldwide perceive the situation awareness requirements and usefulness of social media data in the same way. Second, the usefulness of Twitter data was discussed with the emergency operators based on original tweets collected during a storm event in Germany. However, retweets and replies might also include relevant information and could be examined in future research. Furthermore, it might be conceivable that the perceived usefulness of Twitter data differs depending on the type and severity of the crisis situation as well as the usage patterns of Twitter in a given country. Related to this, future studies could also investigate whether the perceived usefulness of tweets depends on the different stages of emergency management (e.g. preparation, response, and recovery). Third, we proposed a conceptual design based on the insights gained through the goal-directed task analysis and expert interviews. The subject matter experts were not experts on interactive systems, therefore we invited situation awareness and augmented reality experts to provide further feedback on the design. Furthermore, the implementation and evaluation of the design regarding its usefulness for enhancing situation awareness and reducing information overload of emergency operators represents another avenue for further research. Nevertheless, the statements of our interview partners and workshops participants allow us to conclude that the control room work environment constitutes a promising application area for social media and augmented reality technologies.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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Jennifer Fromm is a PhD candidate at the Department of Computer Science and Applied Cognitive Science at the University of Duisburg-Essen, Germany. She received a master's degree in Applied Cognitive and Media Science from the University of Duisburg-Essen, Germany. Her studies focus on the effective use of virtual and augmented reality in meaningful application areas such as crisis management and higher education. Her research has been presented, for example, at the European Conference on Information Systems, the Australasian Conference on Information Systems, and the International Conference on Wirtschaftsinformatik. Her research has been published in journals such as Computers & Education and the International Journal of Information Systems for Crisis Response and Management.

Kaan Eyilmez holds a Bachelor's degree in Applied Cognitive and Media Science and graduated from University of Duisburg-Essen, Germany. He is interested in crisis communication and the usage of augmented and virtual reality.

Melina Baßfeld holds a Bachelor's degree in Applied Cognitive and Media Science and graduated from University of Duisburg-Essen, Germany. She is interested in usability engineering and web design of social media monitoring tools.

Tim A. Majchrzak is professor in Information Systems at the University of Agder (UiA) in Kristiansand, Norway. He also is a member of the Centre for Integrated Emergency Management (CIEM) at UiA. His research comprises both technical and organizational aspects of Software Engineering, often in the context of Mobile Computing. He has also published work on diverse interdisciplinary Information Systems topics, most notably targeting Crisis Prevention and Management. Tim's research projects typically have an interface to industry and society. He is a senior member of the IEEE and the IEEE Computer Society, and a member of the Gesellschaft für Informatik e.V.

Stefan Stieglitz is a professor and head of the research group for Professional Communication in Electronic Media/Social Media at the University of Duisburg-Essen, Germany. In his research, he investigates how to make use of social media data. Moreover, he analyzes user behavior and technology adoption of collaborative informationsystems in organizational contexts. He is director and founder of the Competence Center Connected Organization. Stefan has been an honorary professor at University of Sydney since 2018. His work has been published in reputable journals such as the Journal of Management Information System (JMIS), European Journal of InformationSystems (EJIS), Journal of Information Technology (JIT) and Business & Information Systems Engineering (BISE). In 2016, one of his articles was recognized with the 'AIS Senior Scholars Best IS Publications Award'.

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A SYSTEMATIC REVIEW OF EMPIRICAL AFFORDANCE STUDIES: RECOMMENDATIONS FOR AFFORDANCE RESEARCH IN INFORMATION SYSTEMS

Jennifer Fromm
University of Duisburg-Essen, jennifer.fromm@uni-due.de

Milad Mirbabaie
University of Bremen, milad.mirbabaie@uni-bremen.de

Stefan Stieglitz
Universität Duisburg-Essen, stefan.stieglitz@uni-due.de

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Research in Progress

Fromm, Jennifer, University of Duisburg-Essen, Duisburg, Germany, jennifer.fromm@uni-due.de

Mirbabaie, Milad, University of Bremen, Bremen, Germany, milad.mirbabaie@uni-bremen.de

Stieglitz, Stefan, University of Duisburg-Essen, Duisburg, Germany, stefan.stieglitz@uni-due.de

Abstract

In recent years, there has been an increasing demand to investigate IT-associated organizational change with equal consideration of the materiality of IT artifacts and their human interpretation. Many researchers consider affordances to be a promising theoretical concept that enables a middle ground between technological determinism and social constructivism. However, the transfer of the affordance concept that originated in ecological psychology to the field of Information Systems gave rise to ontological discussions and methodological questions. With our research, we aim to answer the call for more precise methodological guidelines for affordance research. Therefore, we conducted a systematic literature review of empirical affordance studies in Information Systems publication outlets. Our search resulted in 152 relevant articles, from which we analyzed 29 journal articles as part of our research-in-progress. From these articles, we extracted data regarding the concepts of technology type, application area, technology affordances, research design, research methods, and methodological best practices. In our article, we provide insights about the current state of affordance research and derive eight recommendations for conducting affordance research in the field of Information Systems. By doing so, we contribute to a systematic approach for developing affordance-based theories of IT-associated organizational change in the field of Information Systems.

Keywords: Affordance Theory, Methodological Recommendations, IT-Associated Organizational Change, Systematic Literature Review.

1 Introduction

The investigation of IT-associated organizational change always has been among the core topics in Information Systems (IS) research (Mirbabaie, Stieglitz and Volkeri, 2016; Mirbabaie *et al.*, 2019; Stieglitz *et al.*, 2019). In this respect, there has been an increasing demand to investigate this phenomenon with equal consideration of the materiality of IT artifacts and their human interpretation (Orlikowski, 2007; Orlikowski and Scott, 2008). Many researchers consider affordances to be a promising theoretical concept that enables a middle ground between technological determinism and social constructivism (Leonardi and Barley, 2010; Faraj and Azad, 2012; Robey, Anderson and Raymond, 2013). However, the affordance concept originates from ecological psychology and the adaptation of this concept for IS research constitutes an ongoing challenge (Fayard and Weeks, 2014). In particular, it has been difficult to translate the original affordance theory focusing on animals in their natural environment to the study of organizational actors interacting with IT artifacts (Volkoff and Strong, 2017).

The transfer of the affordance concept to the IS field gave rise to ontological discussions but also methodological questions. For example, Seidel, Recker, and Vom Brocke (2013, p. 47) call for *"more precise methodological guidelines"* regarding the identification and operationalization of affordances in IS research. Volkoff and Strong (2017) took a first step in this direction and proposed methodological guidelines for affordance research based on their own experiences in applying the affordance lens. With our research, we aim to extend their work by deriving recommendations based on a systematic literature review of empirical affordance studies in IS research. Hence, we ask the following research questions:

RQ1: What are current issues in empirical affordance research in the field of IS?

RQ2: What are methodological best practices in empirical affordance studies in the field of IS?

By answering these questions, we contribute to a systematic approach for developing affordance-based theories of IT-associated organizational change in the field of IS. To answer these questions, we conducted a systematic literature review following established guidelines (Webster and Watson, 2002; Vom Brocke *et al.*, 2015), as this method has been described as suitable to *"identify the research methods and strategies that are common in an area"* (Vom Brocke *et al.*, 2015, p. 208). A systematic literature review allowed us to analyze current issues in empirical affordance research and collect methodological approaches and best practices that have been used in this research stream. By doing so, we revealed that the field of IS still requires a shared understanding of the affordance concept and derived eight recommendations for conducting empirical affordance research in the IS field.

The remainder of this article is structured as follows: In the next section, we summarize the origin of the affordance concept and the transfer to the IS field. We then describe how we conducted the systematic literature review. Afterwards, we report our results on the current state of affordance research in the IS field and derive recommendations for conducting affordance research. Finally, we summarize our theoretical contribution, address limitations and outline how we will expand our research-in-progress to a journal article.

2 Affordance Theory in the IS Field

In the IS field, it remains a perpetual debate how we can investigate IT-associated organizational change without overemphasizing either the materiality of technology or the human interpretation of IT artifacts (Leonardi and Barley, 2010). Sociomaterialism was suggested as a new research perspective that considers the importance of the *"duality of structure"* meaning the interplay between embedded structures of technologies and emerging structures that arise through social interaction with technology (Orlikowski, 2007; Orlikowski and Scott, 2008). In this regard, Hutchby (2001) proposed a transfer of the affordance concept from ecology to the study of IT artifacts because he argued that it acknowledges both the materiality of technology and the human interpretation of IT artifacts. The term affordance was coined by ecological psychologist Gibson (1979), who questioned existing assumptions about perception and proposed a new theory of visual perception. In his view, animals and humans do not perceive physical properties of surfaces, substances, objects and other animals in their environment, and then deduce what interaction possibilities they offer them. Rather, when animals and humans observe their surroundings, they directly perceive *"what it offers (...), what it provides or furnishes, either for good or ill"* (Gibson, 1979, p. 197). He distinguishes between *positive affordances* and *negative affordances*, for example, a cliff affords walking but also injury if one moves too close to the abyss. In contrast to the similar concept of demand character, affordances are *"always there to be perceived"* independently of the needs of the observer (Gibson, 1979, p. 139). Thus, many different action potentials are offered to animals at any given time, however, the conditions under which these are actualized were not clearly specified in Gibson's initial work. From an ontological discussion among ecological psychologists emerged the shared understanding that affordances have to be perceived before they can be actualized (Chemero, 2003). The perception of an affordance, however, does not necessarily lead to the actualization of the affordance (Stoffregen, 2003). Before these ontological issues were clarified among the ecological psychologists, the affordance concept was already adopted in IS research. This resulted in a contradictory use of affordances in the field of IS. Over time, the relational nature of the affordance concept emerged as a common theme in IS research (Markus and Silver, 2008). The definition of Strong et al. (2014, p. 69) reflects this relational nature by describing an affordance as *"the potential for behavior associated with achieving an immediate concrete outcome and arising from the relation between an artifact and a goal-oriented actor or actors"*. Although the ontological discussion around the affordance concept has progressed, it remains an open question what constitutes *"good"* affordance research from a methodological point of view. A systematic literature review revealed that many affordance studies discussed the concept on a theoretical level or reported results from single case studies (Pozzi, Pigni and Vitari, 2014). This indicates a lack of a unified theoretical understanding of the concept and a lack of methodological guidance for conducting empirical affordance studies. In this regard, Volkoff and Strong (2017) proposed the following six principles for using affordance theory in IS research based on their own experiences in applying the affordance lens as experts in the field: 1) Remember that an affordance arises from the user/artifact relation, not just from the artifact, 2) Maintain the distinction between an affordance and its actualization, 3) focus on the action, not the state or condition reached after taking the action, 4) Select an appropriate level(s) of granularity for the affordances, 5) Identify all salient affordances and how they interact, and 6) Recognize social forces that affect affordance actualization. Volkoff and Strong (2017) derived their principles based on the challenges they personally encountered when applying the affordance concept in IS research. We aim to advance their work by identifying discrepancies and consistencies between affordance theory and affordance research practice in a large sample of empirical affordances studies published in IS outlets. The goal of our research is to derive actionable methodological recommendations based on current research practices that are consistent with affordance theory.

3 Systematic Literature Review

We aimed for a comprehensive review of empirical affordance studies in IS publication outlets. For this reason, we started with a keyword-based search on the electronic database Scopus and limited the search to the IS basket of eight journals[1]. We continued our search in the following collections on the electronic database AISeL: Journals, AIS Conferences, AIS Affiliated Conferences and Other Conferences[2]. To ensure a high coverage of relevant articles, we searched for the keyword *"affordance"* in the abstract and did not limit the timeframe of the search. Our search on 13th August, 2019 yielded 54 articles on Scopus and 399 articles on AISeL. Some IS basket of eight journals were also included on AISeL which led to the removal of 34 duplicate articles. A thorough two-stage exclusion process followed. First, we examined the abstracts of all remaining articles to assess their thematic relevance. Articles were excluded if the abstract contained affordance-related terms, but the context revealed another meaning. For example, sometimes the term *"afford"* occurred in the sense of *"financially affordable"*. Second, we assessed the relevancy of the remaining 260 articles by reading the full text. At this stage, we excluded most articles because affordance-related terms occurred only very few times at the beginning of the paper but were not part of the method, result or discussion sections. As we aimed to analyze how empirical affordance studies were conducted, we also excluded purely theoretical articles but included these in the theoretical background section instead. The selection process resulted in 152 relevant articles, of which 29 were published in IS journals. The results presented in this research-in-progress paper are based on these 29 journal articles and will be enriched once we completed the analysis of the conference articles. An overview about the number of articles at each stage of the selection process can be found in Table 1.

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[1] The IS basket of eight journals include: European Journal of Information Systems, Information Systems Journal, Information Systems Research, Journal of the Association for Information Systems, Journal of Information Technology, Journal of Management Information Systems, Journal of Strategic Information Systems, Management Information Systems Quarterly

[2] The following links provide a complete overview of the publication outlets that are included in the different AISeL collections: Journals (https://aisel.aisnet.org/journals/), AIS Conferences (https://aisel.aisnet.org/conferences/), AIS Affiliated Conferences (https://aisel.aisnet.org/affiliated/), and Other Conferences (https://aisel.aisnet.org/other/).

Database	Search Results	Remaining after Duplicate Check	Relevant Articles (Abstract)	Relevant Articles (Full Text)
Scopus: IS Basket of Eight Journals	54	54	52	26
AISeL: Journals	55	22	5	3
AISeL: AIS Conferences	285	284	166	100
AISeL: AIS Affiliated Conferences	44	44	29	18
AISeL: Other Conferences	15	15	8	5
Sum	**453**	**419**	**260**	**152**

Table 1. Initial Search Results and Number of Relevant Articles after Exclusion Process

To analyze the relevant journal articles, we applied the concept-centric approach as suggested by Webster and Watson (2002). Based on our research questions and theoretical background, we derived initial concepts using a deductive approach and revised them through an iterative data extraction process. From each article, we extracted data regarding the concepts of *technology type*, *application area*, *technology affordances*, *research design*, *research methods,* and *methodological best practices* (see Table 2 for descriptions and examples). The first three concepts were selected because they allowed us to obtain an overview about which technology affordances have already been identified in relation to specific technology types in different application areas. The remaining three concepts were selected because they enabled us to understand which methodological approaches have been predominant in affordance research in the IS field. For all concepts, we extracted the data by marking relevant sections in the articles and transferring the information into a JSON file. During this step, we extracted the concepts exactly as mentioned by the authors of the respective articles. The data was imported to the visualization software Tableau which allowed us to recognize and merge labels that described the same concept as well as to create mappings of different concepts (e.g. *technology type* and *technology affordances*).

Concept	Description	Examples
Technology Type	Describes of which technology type affordances have been identified. Many articles identified affordances of specific applications (e.g. Facebook) or technology subtypes (e.g. social networking sites). These were merged by selecting an overarching technology type mentioned in these articles (e.g. social media).	social media, health information technology, green information systems, …
Application Area	Describes in which context the affordances of a specific technology have been researched. Similar research contexts were merged (e.g. social movements and collective action).	health care, collective action, organizational innovation, …
Technology Affordances	Includes all affordances the authors of the relevant articles themselves described as affordances. We decided against including only affordances that fit a specific definition because we were interested in the authors' understanding of affordances.	accessibility, add-ons affordance, broadcasting, communicating with patients, …
Research Design	Based on the applied research strategies and methods, we classified the research design as qualitative, quantitative or mixed-methods following the definitions of Creswell and Creswell (2007). Articles focusing on the development of an artifact were classified as design-oriented research (Fallman, 2003).	empirical qualitative, empirical quantitative, mixed-methods and design-oriented research
Research Methods	All research methods mentioned by the authors of the relevant articles were extracted. Similar methods were merged (e.g. regression analysis includes linear and logarithmic regression analysis).	case study, interviews, grounded theory, survey, regression analysis, …
Methodological Best Practices	All text passages in which the authors described how they methodologically incorporated the affordance concept in their research. This includes best practices of collecting and analyzing data about affordances as well as reporting the results of affordance research.	labeling affordances as gerunds, distinguishing between basic and higher-level affordances, …

Table 2. Description of Concepts and Examples

4 Preliminary Findings

Our search was not limited to a specific time period, but Figure 1 reveals when IS journals started publishing empirical affordance studies. The first journal article describing an empirical affordance study appeared in 2011. While the initial articles have been published in Management Information Systems Quarterly (MISQ), other IS journals started to publish empirical affordance studies in 2014. With seven journal articles, Information Systems Journal (ISJ) published the most affordance studies so far. Overall, we can observe an increase in empirical affordance studies over the years indicating that the affordance lens will remain important in the future.

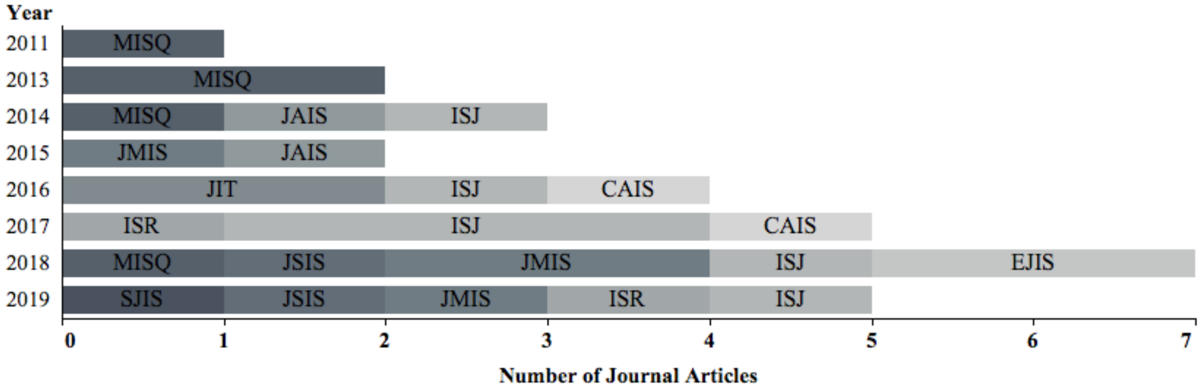

Figure 1. Number of Journal Articles per Year

As can be seen in Figure 2, the large majority of journal articles applied an empirical qualitative research design (*N*=22). In 86% of the qualitative research articles, the authors used either a case study or field study methodology and mentioned data collection methods such as interviews, document analysis, observations, focus groups, artifact analysis, and usage data analysis. The remaining seven articles conducted either empirical quantitative (*N*=4), mixed-methods (*N*=2) or design-oriented research (*N*=1). In the few quantitative research articles, all authors developed new instruments to measure the affordance of a specific technology type in a specific application area. This indicates a lack of established and validated measurement instruments that can be used in surveys across quantitative studies.

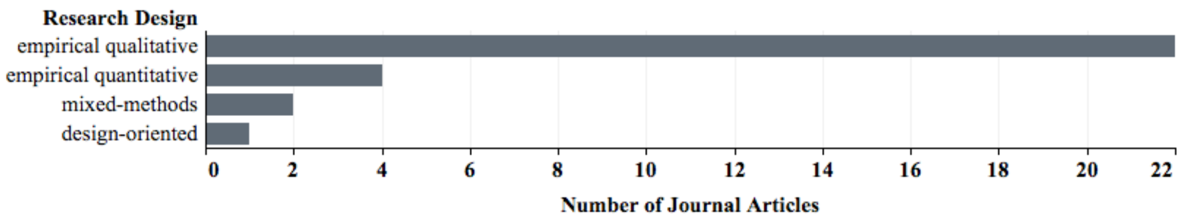

Figure 2. Research Design of Empirical Affordance Studies

A mapping of technology type and application area (see Figure 3) reveals that 28% of all articles investigated the affordances of social media (*N*=7) in various application areas such as collective action (*N*=3), crisis management (*N*=1), cyberbullying (*N*=1), knowledge management (*N*=1), and organizational socialization (*N*=1). Furthermore, 14% of all journal articles examined the affordances of health information technology in health care (*N*=4). Studies considering the affordances of green information systems, information technology in general, and multi-sided platforms accounted for 7% each. The following technologies occurred in only one article: wearables, student information systems, simulation technology, sensemaking support systems, office software, financial technology, communication technology, cloud computing, and big data analytics. Two articles considered the affordances of multiple technologies at once.

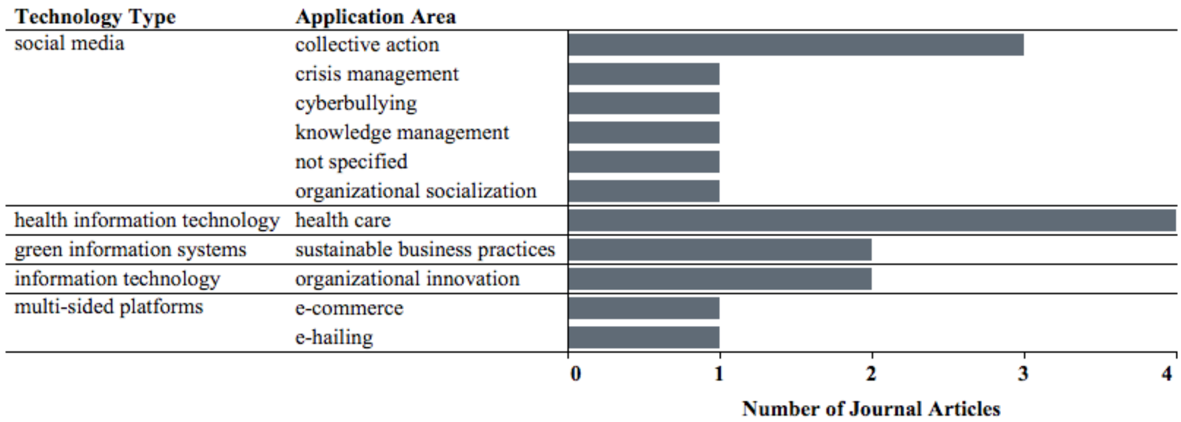

Figure 3. Mapping of Technology Type and Application Area (includes all technology types that occurred in more than one article)

In total, the authors of the 29 analyzed journal articles mentioned 168 different technology affordances. Of these, 67 affordances refer to social media – the technology type that most empirical studies in our sample investigated. Our results reveal that the large majority of social media affordances occurred in exactly one article (*N*=60). Only seven affordances have been used in more than one article: *association* and *editability* (*N*=3) as well as *meta-voicing*, *visibility*, *network-informed associating*, *experimentation*, and *persistence* (*N*=2). Our findings indicate that there seems to be lack of established affordances for each technology type that can be reused across several studies. Instead most studies add new affordances to the already exhaustive list. Furthermore, there does not seem to exist a shared practice of labelling affordances as some authors prefer using nouns (e.g. association) while others prefer using verbs (e.g. associating). This complicates distinguishing affordances that should describe action potentials from technology capabilities, features, uses, and usage outcomes. In addition, the mentioned affordances are often defined in a similar way but refer to different levels of abstraction (e.g. visibility and organizational visibility). Altogether our findings illustrate the need for a consolidation of affordances for each technology type to provide a smaller set of truly unique affordances that actually describe action potentials. We consider this an important step towards a conceptual basis for future empirical affordance studies.

5 Recommendations for Affordance Research

After analyzing the current state of empirical affordance research, we examined the extracted text passages in which the authors described how they methodologically incorporated the affordance concept in their research. By synthesizing the methodological best practices, we derived eight recommendations for conducting empirical affordance studies in the IS field.

1) Aim for a mid-range theory of IT-associated organizational change: Strong et al. (2014) emphasize the need for mid-range theories of IT-associated organizational change that allow us to derive actionable recommendations for practice. In addition, Volkoff and Strong (2013) consider the affordance concept an important basis for mid-range theories that provide explanations for organizational change associated with a specific technology but also allow for a certain degree of generalizability. Thus, we conclude that affordance-based theories should aim to explain how a specific type of technology (e.g. social media) leads to organizational change in specific application areas (e.g. knowledge management).

2) Apply critical realism as a research paradigm: Volkoff and Strong (2013) suggest to remember the critical realist roots of the affordance concept and consider critical realism the appropriate research paradigm for the development of affordance-based theories of organizational change. Critical realists assume that material and social structures exist independently from our perception and provide potentials for behaviors called mechanisms. These generate events and outcomes of which only a subset can be observed (Bhaskar, 1998). Critical realists are interested in explaining the observable outcomes (e.g. increased job performance) through the introduction of new structures (e.g. implementation of a new system) by uncovering the underlying generative mechanisms (Mutch, 2010). Volkoff and Strong

(2013) suggest uncovering these generative mechanisms through the process of retroduction which is a creative process in which multiple explanations are proposed that might be able to produce the observed outcomes (Sayer, 2004). In this regard, Bygstad, Munkvold, and Volkoff (2016) developed a stepwise framework for critical realist data analysis which involves the identification of affordances through retroduction. Two further studies in our sample have applied the critical realist research paradigm (Leidner, Gonzalez and Koch, 2018; Leonardi, Bailey and Pierce, 2019).

3) Separate affordances from technology features, use, and usage outcomes: There does not seem to exist a shared understanding on how to clearly differentiate between affordances, technology features, use, and usage outcomes. For example, Du et al. (2019) argue that the affordances identified by Strong et al. (2014) are in fact outcomes while the affordances identified by Majchrzak et al. (2013) are rather direct uses of technology. To clarify their own view, many authors included a table in their article in which they clearly describe what they consider to be the relevant IT features, affordances (action potentials), affordance actualizations (usage), and immediate concrete outcomes resulting from affordance actualization (Strong et al., 2014; Tan et al., 2017; Leidner, Gonzalez and Koch, 2018; Du et al., 2019; Karlsen et al., 2019; McKenna, 2019). Furthermore, Strong et al. (2014) suggest naming affordances as gerunds that describe the actions required to actualize the affordances.

4) Consider the relational nature of the affordance concept: According to the accepted definition of Strong et al. (2014) affordances are *"arising from the relation between an artifact and a goal-oriented actor or actors"*. Therefore, some researchers include a detailed description of the actors' goals and features of the artifact under study (Burton-Jones and Volkoff, 2017; Du et al., 2019; Karlsen et al., 2019). Other researchers consider the relational nature of the affordance concept by mapping affordances to specific IT features (Karahanna et al., 2018; Krancher, Luther and Jost, 2018; Lehrer et al., 2018; Leidner, Gonzalez and Koch, 2018; Leonardi, Bailey and Pierce, 2019; McKenna, 2019). Mapping affordances to user types is another approach emphasizing that the affordances of one and the same technology are perceived and actualized differently by specific user types (Leidner, Gonzalez and Koch, 2018; McKenna, 2019). Both approaches allow for a generalizability of affordances to other technologies with similar features or user groups with similar characteristics. The relational nature of the affordance concept also complicates the development of established measurement instruments. In this regard, Grgecic, Holten, and Rosenkranz (2015) state that items to measure affordances have to be developed for each new combination of IT artifact and user group under study.

5) Show the interrelations and interactions between multiple affordances: Several researchers distinguish between basic and higher-level affordances (Volkoff and Strong, 2013; Strong et al., 2014; Krancher, Luther and Jost, 2018; Leidner, Gonzalez and Koch, 2018; Du et al., 2019). They assume that the actualization of basic affordances produces outcomes which in turn enable the actualization of higher-level affordances. Building upon this assumption, Thapa and Sein (2017) propose the trajectory of affordance construct that also reflects the need for facilitating conditions before higher-level affordances can be actualized. To clarify interrelations between multiple affordances, some authors suggest creating affordance strands by grouping affordances that are related to similar immediate concrete outcomes (Volkoff and Strong, 2013; Leidner, Gonzalez and Koch, 2018). Linking these affordance strands to higher-level outcomes in a second step allows to abstract generative mechanisms that explain IT-associated organizational change (Volkoff and Strong, 2013; Bygstad, Munkvold and Volkoff, 2016; Leidner, Gonzalez and Koch, 2018). Other researchers suggest that organizational level outcomes can be explained by aggregating the immediate concrete outcomes of individual affordance actualizations. Such collective actualization processes can be visualized by using affordance networks (Burton-Jones and Volkoff, 2017) and affordance dependency diagrams (Strong et al., 2014; Karlsen et al., 2019).

6) Identify contextual factors inhibiting or enabling affordance actualization: Many authors provide a detailed description of their research context and identified contextual factors inhibiting or enabling affordance actualization such as work environment characteristics, individual competencies, skills, and attitudes, as well as IT features and infrastructure (Jung and Lyytinen, 2014; Strong et al., 2014; Bygstad, Munkvold and Volkoff, 2016; Burton-Jones and Volkoff, 2017; Thapa and Sein, 2017; Krancher, Luther and Jost, 2018; Du et al., 2019; Karlsen et al., 2019; Leonardi, Bailey and Pierce, 2019).

7) Analyze the paradoxical tension between technology affordances and constraints: Although many studies considered contextual factors that both inhibit and enable affordance actualization, only three studies analyzed both technology affordances and constraints (Leonardi, 2011; Ciriello, Richter and Schwabe, 2018; Mettler and Wulf, 2018). In particular, Ciriello, Richter, and Schwabe (2018) emphasize that the parallel perception of affordances and constraints creates paradoxical tensions that might result in unexpected actualization outcomes. Furthermore, Leonardi (2011) proposes the imbrication metaphor to explain how the perception of affordances leads to a change of routines while the perception of constraints leads to changes of technology.

8) Apply affordances identified in previous literature: In our sample, the authors of ten articles applied affordances identified in previous research (Nan and Lu, 2014; Chatterjee et al., 2015; Argyris and Ransbotham, 2016; Hanelt, Busse and Kolbe, 2017; Tim et al., 2017; Ciriello, Richter and Schwabe, 2018; Karahanna et al., 2018; Mettler and Wulf, 2018; Seidel et al., 2018; Chan, Cheung and Wong, 2019). Furthermore, Karahanna et al. (2018) conducted a systematic review of social media affordances and described a process of consolidating similar affordances. Similar work consolidating the affordances of other technology types might be beneficial to allow for generalizability of results across studies using the same type of technology.

6 Summary and Further Steps

The purpose of our research was to develop recommendations for affordance research in the field of IS to pave the way for empirical studies applying this theoretical lens in the future. The affordance concept is considered a promising concept for theorizing IT-associated organizational change that acknowledges both the materiality of IT artifacts and their human interpretation. However, since the affordance concept does not have its origin in the field of IS, there does not exist a systematic approach for developing affordance-based theories of IT-associated organizational change, yet. Therefore, we conducted a systematic literature review of empirical affordance studies in IS publication outlets to synthesize methodological best practices. In this research-in-progress article, we presented the insights we already gained through the analysis of 29 journal articles. We consolidated the methodological approaches and best practices that have been used in these articles to derive eight recommendations for affordance research in the IS field. The subjective decisions that have to be made when conducting systematic literature reviews, such as the selection of keywords, databases and exclusion criteria, represent a limitation of our study. In total, however, we have identified 152 relevant articles and therefore assume that we have a profound basis for continuing our research.

Our next step will be to complete the analysis of the remaining 123 conference articles and to expand our set of recommendations. When continuing our research-in-progress, we will take our research one step further and derive a systematic approach for developing affordance-based theories of IT-associated organizational change. Within the scope of this article, we collected different existing methodological approaches and best practices. Extending our research allows us to add a thorough discussion of these different approaches to provide other IS researchers with actionable recommendations and a systematic approach for affordance-based theory development. When our analysis is complete, we will also have an exhaustive list of already identified affordances associated with specific technology types in IS research. We aim to use this list to consolidate similar affordances with different labels or at different levels of abstraction in a similar way as Karahanna et al. (2018) have already done for social media affordances. This way, we will be able to contribute a list of truly unique affordances for each technology type that can serve as a starting point for future studies of the same technology type (e.g. health information technology affordances, green information systems affordances, and so on). By doing so, we contribute to the generalizability of findings across studies and enable the development of quantitative measurement instruments. Nevertheless, the consolidated affordances will still be perceived and actualized in various ways by different user groups.

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The DATA BASE for Advances in Information Systems

Virtual Reality in Digital Education: An Affordance Network Perspective on Effective Use Behavior

Jennifer Fromm
University of Duisburg-Essen

Stefan Stieglitz
University of Potsdam

Milad Mirbabaie
Paderborn University

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Jennifer Fromm
University of Duisburg-Essen

Stefan Stieglitz
University of Potsdam

Milad Mirbabaie
Paderborn University

Abstract

Virtual reality promises high potential as an immersive, hands-on learning tool for training 21st century skills. However, previous research revealed that the mere use of digital tools in higher education does not automatically translate into learning outcomes. Instead, information systems studies emphasized the importance of effective use behavior to achieve technology usage goals. Applying the affordance network approach, we investigated what constitutes effective usage behavior regarding a virtual reality collaboration system in digital education. Therefore, we conducted 18 interviews with students and observations of six course sessions. The results uncover how affordance actualization contributed to the achievement of learning goals. A comparison with findings of previous studies on other information systems (i.e., electronic medical record systems, big data analytics, fitness wearables) allowed us to highlight system-specific differences in effective use behavior. We also demonstrated a clear distinction between concepts surrounding effective use theory facilitating the application of the affordance network approach in information systems research.

Keywords: Virtual Reality; Effective Use Behavior; Affordance Network Approach; Digital Education; Qualitative Research.

Introduction

With the advance of digitalization, the goals of educational institutions increasingly shifted toward training students in 21st century skills (OECD, 2019). Virtual reality (VR) has been emphasized as an immersive, hands-on learning tool with the potential to improve 21st century skills such as digital literacy, creative thinking, communication, collaboration, and problem solving (Papanastasiou et al., 2019). However, a meta-analysis covering forty years of research highlighted that the use of digital tools in teaching does not automatically translate into the achievement of learning goals (Tamim et al., 2011). Instead, information systems scholars emphasized the importance of effective use referring to the type of use that helps achieve the goals for using the system (Burton-Jones & Grange, 2013).

Previous studies demonstrated that actual usage behavior plays a decisive role in goal achievement (e.g., Schlagwein & Hu, 2017; Lin et al., 2019; Ghasemaghaei & Turel, 2020). For example, Schlagwein and Hu (2017) proposed that only certain types of social media use contribute to the achievement of organizational knowledge management goals. A study on big data analytics revealed that knowledge hiding behaviors prevented

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organizations from improving decision-making quality (Ghasemaghaei & Turel, 2020). Another study quantified the impact of effective use of an electronic medical record system and found an improvement of up to 0.43 percentage points in healthcare quality (Lin et al., 2019). Despite the importance of effective use behavior, information systems research mainly focused on external factors influencing effective use (e.g., Surbakti et al., 202; Weeger et al., 2014), adaptation and learning as drivers of effective use (e.g., Haake et al., 2015; Gnewuch et al., 2016) and the link between effective use dimensions and performance (e.g., Marchand & Raymond. 2018; Campbell & Roberts, 2018). Hence, we examine the following research question:

RQ: *Which behavior constitutes the effective use of virtual reality in digital education?*

To gain insights, we conducted a qualitative study in the context of a VR course at a university designed to promote competencies such as digital literacy and collaboration skills. We carried out the study over a period of four months, following the affordance network approach (Burton-Jones & Volkoff, 2017). In total, we conducted 18 interviews with the nine course participants and observations of six course sessions, with data collection taking place at two points in time. Using qualitative content analysis (Mayring, 2015), we analyzed the results to map effective use behavior in the form of an affordance network.

By answering the research question, we contribute a context-specific theory of effective use behavior regarding VR in a collaborative learning setting. Context-specific theories increase the potential for direct applicability in practice, and thus provide more actionable insights for practitioners (Benbasat & Zmud, 1999; Hong et al., 2014). Our study is among the first to examine effective use behavior with respect to a VR collaboration system, allowing us to demonstrate the unique nature of effective use behavior compared to other types of information systems already studied (e.g., electronic medical record systems, big data analytics). Furthermore, we clearly delineate arbitrary concepts surrounding effective use theory, which facilitates the application of the affordance network approach in information systems research. For educators, our results provide meaningful insights into how to guide usage behavior of students in a direction that helps them to achieve learning goals.

Next, we summarize related work on VR in digital education and introduce effective use theory as well as previous studies on effective use. Then, we describe how we applied the affordance network approach. Afterward, we present our findings, starting with the components that constitute effective use behavior in our research context and ending with the final affordance network. Lastly, we discuss our findings considering effective use theory and previous research, address limitations and propose avenues for future research.

Theoretical Background and Related Work

Virtual Reality in Digital Education

VR can be defined as *"the sum of the hardware and software systems that seek to perfect an all-inclusive, immersive, sensory illusion of being present in another environment"* (Biocca & Delaney, 1995, p. 63). The distinguishing characteristics of VR are its high levels of immersion, presence, and interactivity (Mütterlein, 2018). Immersion can be understood as an objective and measurable depiction of the provided features for creating a virtual illusion (Slater & Wilbur, 1997). However, immersion can also be seen as *"a psychological state characterized by perceiving oneself to be enveloped by [...] an environment that provides a continuous stream of stimuli and experiences"* (Witmer & Singer 1988, p. 227). Following the arguments of Mütterlein (2018), we understand immersion as a psychological experience limited by the technological capabilities of a system. Presence has a psychological and subjective character, since it is the *"experience of being in one place or environment, even when one is physically situated in another"* (Witmer & Singer, 1998, p. 225). Interactivity describes *"the extent to which users can participate in modifying the form and content of a mediated environment in real time"* (Steuer, 1992, p. 84).

Digital education is a well-known VR application area, especially since portable and low-cost applications are being made available (Hodgson et al., 2015). A recent systematic literature review provided a comprehensive overview about VR applications in higher education and identified engineering education, virtual laboratories, and foreign language learning as common application scenarios (Radianti et al., 2020). First studies also combined flipped classrooms with immersive technologies and showed enhancing effects on the teaching approach (Ferrer-Torregrosa et al., 2016; Im et al., 2019). In these application scenarios, VR has been shown to provide benefits, such as improved learning outcomes, more realistic experiences, as well as an increased intrinsic motivation and learning interest (Chavez & Bayona, 2018; Jensen & Konradsen, 2018). Previous research indicated that a higher level of immersion might further enhance positive learning effects (Hamilton et al., 2021). Furthermore, teachers described perceived advantages such as facilitation of participation, decrease of language barriers, or flexibility of learning pace (Solomon et al., 2019). However, recent studies highlighted challenges related to the effective use of VR in digital education, such as a lack of knowledge and skills, high initial learning curve, and reluctance to integrate new technology into curricula (Alfalah et al., 2018; Solomon et al., 2019; Fransson et al., 2020). To address these challenges, research on the effective use of VR can be supportive. While current research serves knowledge about the opportunities and barriers in different educational contexts, considering effective use provides knowledge on the successful implementation of VR in digital education.

Effective Use Theory

Assuming that mere system usage does not result in desired benefits, researchers proposed the concept of effective use, referring to *"using a system in a way that helps attain the goals for using the system"* (Burton-Jones & Grange, 2013, p. 633). When developing the concept, Burton-Jones and Grange (2008) expected it to be applicable to three types of information systems: (1) *Reporting systems* such as accounting systems are data-base driven and provide *information about reality* because they offer information about states in the world. (2) *Planning systems* such as decision support systems contain *information for reality* enabling users to take actions. (3) *Recording systems* such as video conferencing tools directly represent *information as reality* (Burton-Jones & Grange, 2008). Followingly, VR can be classified as the latter, because users are experiencing interaction as real, although VR offers just a virtual representation.

The concept of effective use was developed based on representation theory which describes the main purpose of information systems as providing users with faithful representations of real-world systems (Wand & Weber, 1995). Burton-Jones and Grange (2013) proposed that three hierarchical dimensions indicate to what extent users experience effective use: First, users need unrestricted access to representations, which is called *transparent interaction* (Burton-Jones & Grange, 2013). For instance, users of an educational VR application should not be prevented from viewing a 3D model by complex controls. Moreover, representations must faithfully depict the state of the real-world system, also called *representational fidelity* (Burton-Jones & Grange, 2013). This would mean that the 3D model is displayed without significant differences from its appearance in the real-world. Lastly, users should be able to perform *informed action* based on representations (Burton-Jones & Grange, 2013). For example, the 3D model could enable students to solve an assignment through a better understanding of the subject.

Furthermore, Burton-Jones and Grange (2013) proposed *learning and adaptation as two drivers* enhancing effective use: First, users can adapt the system's representations or access to them. For example, users could edit the 3D model to better resemble the real-world object or use a VR headset providing a better resolution. Second, users can learn about the system, the represented domain, or how to leverage representations (Burton-Jones & Grange, 2013). For instance, users could learn about the VR system controls, the learning subject, or how to read 3D models. Additionally, researchers suggested that *influencing factors* such as user characteristics, system properties, and organizational context can restrict or enhance effective use (Surbakti et al., 2020; Weeger et al., 2014). However, Burton-Jones and Volkoff (2017) argued that *effective use behavior* remains a black box and proposed the affordance network approach allowing researchers to address this research gap.

The Affordance Concept and the Affordance Network Approach

The idea behind the affordance network approach is understanding effective use behavior in terms of the successful realization of action potentials (affordances) leading to desired outcomes (Burton-Jones & Volkoff, 2017). The affordance concept was introduced by ecological psychologist Gibson (1979) who researched how animals perceive the action potentials of their environment. In information systems, researchers perceived the affordance concept as promising to consider the influence of a technology's materiality on routines without being deterministic (Leonardi & Barley, 2008; Leonardi, 2011). This means that the outcome of technology use is neither determined by the material properties of technology nor by human actions (Markus & Rowe, 2018). Instead, technology structures can afford or constrain certain human actions, while humans can also alter technology structures, organizational structures, and group structures to achieve their goals (Majchrzak et al., 2000). Affordances are understood as a relational concept, emerging from the relationship between individual users and technology (Markus & Majchrzak, 2012). This relational nature is also reflected in the definition by Markus and Silver (2008, p. 622) who defined affordances as *"the possibilities for goal-oriented action afforded to specified user groups by technical objects"*. The realization of affordances is called actualization and results in immediate concrete outcomes (Strong et al., 2014).

In the application of the affordance concept, several researchers have emphasized the importance to distinguish more clearly between technology features, affordances as action potentials, and outcomes of affordance actualization (Leidner et al., 2018; Fromm et al., 2020). In this regard, Evans et al. (2017) proposed three threshold criteria that researchers should assess before calling something an affordance: (1) whether the affordance is dynamic (i.e., users might agree on features but might perceive different affordances depending on their goals), (2) whether the affordance can be associated with multiple outcomes (i.e., the same affordance might result in different outcomes for individual users), and (3) whether the affordance has variability (i.e., affordances can vary in the ease with which they are actualized based on individual users' capabilities).

Based on the affordance concept, Burton-Jones and Volkoff (2017, p. 482) suggested five steps for developing context-specific theories of effective use behavior: *"(1) understand the nature of the IT artifact in question, (2) identify the relevant actors and their ultimate goals, (3) determine the potential actions and immediate concrete outcomes the IT artifact enables for the actors (the affordances), (4) identify the dimensions of effective actualization, and (5) map out the network of affordances and the connections and feedback loops among the affordance-outcome units"*. Brought into relation, all components build an affordance network. Contextualization is important because the specifics of the IT artifact and usage context can have a large impact on behavior (Johns, 2006; Bamberger, 2008). If context is not considered, this can lead to inconsistent results across studies (Johns, 2006; Whetten, 2009). As Boiney (1998, p. 343) already pointed out, *"The same technology will not provide the same results with each group and in each setting"*. Affordance networks in particular cannot simply be transferred to other contexts because the emergence of affordances depends on the specifics of the IT artifact and user group (Markus & Silver, 2008). Furthermore, the interrelations between affordance-outcome units and dimensions of effective actualization might differ across contexts (Burton-Jones & Volkoff, 2017). Thus, the development of context-specific theories can lead to richer and more accurate results facilitating the generalization of findings over time (Bamberger, 2008). Furthermore, considering the specific context in theorizing increases the potential for direct applicability and relevance for practice (Benbasat & Zmud, 1999; Hong et al., 2014).

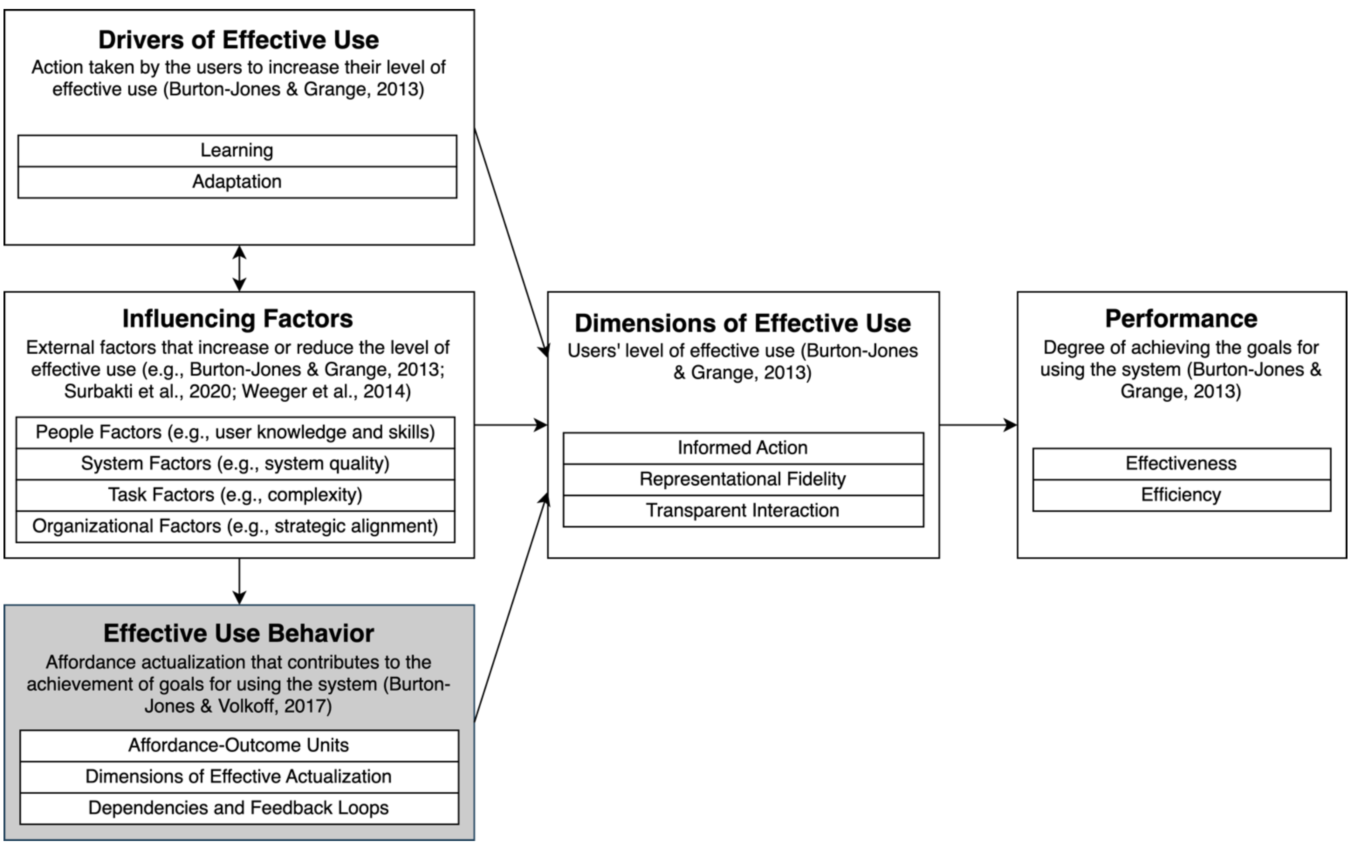


Figure 1. Theoretical Conceptualization

To clearly delineate the concepts surrounding effective use theory, Figure 1 provides an overview of the theoretical conceptualization underlying this study. With our study, we contribute to a better understanding of effective use behavior (highlighted in gray) of recording systems such as VR in digital education. As we will demonstrate in the following literature review section, previous research mainly applied the affordance network approach to reporting and planning systems (e.g., electronic medical record systems, big data analytics). The few studies focusing on effective use behavior with regarding to recording systems (e.g., social networks, collaborative mobile apps) did not apply the affordance network approach, and thus it is still unclear whether and how this approach is applicable to this type of information systems. For example, it is conceivable that affordance-outcome units would need to have a different structure or that other dimensions of effective actualization are relevant for these systems.

Literature Review on Effective Use

Several information systems studies built upon effective use theory. For instance, researchers verified the effective use dimensions (Marchand & Raymond, 2018) and adapted them for specific contexts such as emergency management (Bonaretti & Piccoli, 2018; Fischer-Preßler et al., 2020). Other researchers developed quantitative measures for the dimensions (Haake et al., 2018; Campbell & Roberts, 2018). Furthermore, studies identified informed action as a significant predictor of job performance, while representational fidelity and transparent interaction had no significant effect (Marchand & Raymond, 2018; Campbell & Roberts, 2018). Other studies focused on the drivers of effective use. Studies investigated the adaptation of technologies such as enterprise systems (e.g., Haake et al., 2015; Lauterbach et al., 2014; Li et al., 2017). For example, Lauterbach et al. (2014) identified four adaptation modes and Li et al. (2017) showed an enhancing effect of workarounds. Furthermore, Gnewuch et al. (2016) identified different learning mechanisms during the introduction of enterprise systems. Previous research also considered influencing factors such as users' knowledge and skills, system quality (Surbakti et al., 2020), and functional misfits between system and organization (Weeger et al., 2014; Eden et al., 2019).

Recently, more studies focused on effective use behavior. Burton-Jones and Volkoff (2017) demonstrated the affordance network approach in a study on the implementation of an electronic medical record system. They identified affordance-outcome units each consisting of a single affordance and a resulting outcome with strong dependencies between units (Strong et al., 2014). The affordance network also depicted differences in how affordances were actualized, which were termed *dimensions of effective actualization* (Burton-Jones & Volkoff, 2017). For example, some users entered data inconsistently, which hindered effective use, while consistent data input enhanced effective use (Burton-Jones & Volkoff, 2017). Another study also highlighted the importance of consistency regarding the use of electronic medical record systems (Eden et al., 2018). Abouzahra and Ghasemaghaei (2022) applied the affordance network approach to the effective use of fitness wearables revealing how users could reach three hierarchical goals through affordance actualization. However, they found that some users did not reach their ultimate goal, since influencing factors such as their perceived physical capability hindered them at actualization.

Although they did not apply the affordance network approach, some studies examined effective use behavior through an affordance lens (Beach & O'Brien, 2015; Tim et al., 2020; Jayarathna et al., 2020; Zeng et al., 2020). Two studies distinguished between several phases in an analytics-driven transformation and found that effective use behavior is characterized by the actualization of different affordances in each phase (Tim et al., 2020; Zeng et al., 2020). Furthermore, Jayarathna et al. (2020) revealed in a study on social media for collaborative learning that the actualization of four affordances (i.e., collaboration, communication, content sharing, self-presentation) positively influenced the perception of learning goal achievement. Another study in an educational context examined how the actualization of four mobile app affordances (i.e., multimodality, collaboration, interactivity, connectivity) supported 6th graders in their ability to engage in causal reasoning (Beach & O'Brien, 2015).

Other studies did not focus on effective use behavior but still identified affordances that served as a foundation for building the affordance network in our study. A recent literature review found that empirical studies on VR in an educational context often focused on the create-ability, navigability, and interactivity affordances of VR (Dincelli & Yayla, 2022). Furthermore, Steffen et al. (2019) compared the affordances of physical reality, augmented reality, and VR, where VR in particular allowed to reduce negative aspects of the physical world (e.g., physical and emotional risks), to recreate existing aspects of the physical world (e.g., collaboration) and to create aspects that do not exist in the physical world (e.g., overcome time-space linearity). Also, Shin et al. (2017) investigated VR affordances (i.e., presence, immersion, empathy, embodied cognition) and how they affected technology acceptance in a learning context. Other studies investigated which cues could signal the interactivity affordance of visualizations for learning purposes (Patwardhan & Murthy, 2015; Boy et al., 2016). Several other studies did not directly focus on VR or the learning context but examined collaborative technologies such as social media rendering them also relevant for our study since Spatial is a collaborative VR application (O'Riordan et al., 2012; Treem & Leonardi, 2012; Leidner et al., 2018; Karahanna et al., 2018). Additional affordances identified in these studies were self-presentation (Suh, 2017; Karahanna et al., 2018), relationship formation (Karahanna et al., 2018; Leidner et al., 2018), content aggregation (O'Riordan et al., 2012), and persistence (Treem & Leonardi, 2012; Karahanna et al., 2018).

Research Gap

In Table 1, we provide an overview about the above-mentioned studies building on effective use theory. Based on the current state of research, we identified two research gaps that we address with our study.

First, recent studies increasingly examined effective use behavior (Beach & O'Brien, 2015; Burton-Jones & Volkoff, 2017; Eden et al., 2018; Tim et al., 2020; Zeng et al., 2020; Jayarathna et al., 2020; Abouzahra & Ghasemaghaei, 2022). However, some studies focused on affordances and the associated outcome, goal, or transformation stage, but neglected dependencies between affordance-outcome units and dimensions of effective actualization (Beach & O'Brien, 2015; Tim et al., 2020; Zeng et al., 2020; Jayarathna et al., 2020). This neglects that the mere actualization of affordances does not already represent effective use, but that it also depends on how these are actualized and in which order, leading to an incomplete picture of effective use behavior. To get a holistic understanding, we apply the affordance network approach considering the individual components, but also the relationships between them and dimensions of effective actualization.

Second, previous studies examined effective use behavior regarding reporting and planning systems in enterprise or healthcare contexts (i.e., fitness wearables, electronic medical record systems, big data analytics). However, only two studies focusing on social networks and a mobile app for learning purposes addressed effective use behavior regarding recording systems in digital education (Beach & O'Brien, 2015; Jayarathna et al., 2020). Social networks and collaborative mobile apps can be classified as recording systems, since these platforms directly represent communication as reality (Burton-Jones & Grange, 2008). Applying the approach in the context of VR in digital education allows us to compare the results with studies on other types of information systems and contribute to the understanding of system-specific differences in effective use behavior.

Table 1. Effective Use Theory: Research Overview

Paper	Technology	System Type	Focus
Lauterbach et al. (2014)	Banking system	RE	DR
Weeger et al. (2014)	Hospital information system	RE / PL	IF
Beach & O'Brien (2015)	Mobile app	RC	BE
Haake et al. (2015)	Product information management system	RE	DR
Gnewuch et al. (2016)	Enterprise systems in general	RE / PL	DR
Burton-Jones and Volkoff (2017)	Electronic medical record system	RE / PL	BE
Li et al. (2017)	Supply chain management system	RE / PL	DR
Bonaretti and Piccoli (2018)	Emergency management system	PL	DI
Eden et al. (2018)	Electronic medical record system	RE / PL	BE
Haake et al. (2018)	Banking system	RE	DI
Marchand and Raymond (2018)	Performance measurement and management system	PL	DI
Campbell and Roberts (2019)	Analytic decision support system	PL	DI
Eden et al. (2019)	Electronic medical record system	RE / PL	IF
Fischer-Preßler et al. (2020)	Emergency management system	PL	DI
Jayarathna et al. (2020)	Social media	RC	BE
Surbakti et al. (2020)	Big data analytics	PL	IF
Tim et al. (2020)	Big data analytics	PL	BE
Zeng et al. (2020)	Big data analytics	PL	BE
Abouzarah and Ghasemaghaei (2021)	Fitness wearables	RE	BE

Note: RE: Reporting system, PL: Planning system, RC: Recording system, DI: Dimensions, DR: Drivers, IF: Influencing Factors, BE: Behavior. The papers are listed in chronological order.

Due to the unique characteristics of VR, we assume that findings of previous effective use studies cannot be applied to our research context. For example, the high degree of immersion allows users to tune out the physical world and focus more on the learning content being delivered within the virtual world. At the same time, however, VR also offers high distraction potential, as virtual environments often allow for many interaction possibilities that cannot only be used to fulfill learning tasks. However, compared to other collaborative systems, each user also has a physical presence in the virtual world, which is why it is immediately visible to other users if they are distracted or multitasking. In a video conference with breakout rooms, for example, it is possible to pursue distracting activities in a second browser tab comparatively unnoticed. These differences make it interesting to investigate effective usage behavior in relation to VR in digital education.

Research Design

Research Context

The study was conducted in the context of an information systems lecture titled *Communication & Collaboration Systems* and was part of the bachelor's program at a German university. In this lecture, students should learn about the challenges and success factors for organizations associated with the introduction of communication and collaboration systems such as enterprise social media. In this context, students learned to apply information systems theories about technology adoption, the spread of innovations, media selection, and the design of workspace awareness by developing their own strategies for the introduction of new technologies. Since the course also aimed to improve students' collaboration skills, they were asked to solve three tasks in each session through discussion and group work.

The lecture consisted of nine sessions, which lasted between sixty and ninety minutes. The course was designed as a flipped classroom focusing on the active participation of students and ended with a written exam. Nine students participated in the lecture from their homes using the collaborative VR application Spatial and the stand-alone VR headset *Meta Quest*. The tasks were based on the revised taxonomy of learning objectives (Krathwohl, 2002), which hierarchically orders six learning objectives according to their cognitive complexity.

Before each session, we uploaded working sheets to the course management system. These sheets contained reading material (i.e., enterprise blog articles, scientific journal articles) and guiding questions. After reading the material, the students were expected to have internalized the theoretical basics corresponding to the lower-level cognitive domains of knowledge and comprehension (Krathwohl, 2002). The in-class tasks were designed in a way that students could reach the higher-level cognitive domains of application, analysis, evaluation, and creation (Table 2). The tasks were solved in small groups and results were discussed in the plenum.

Recruiting and Preparation

The students eligible for participation in the course were contacted via email. Due to the limited number of available VR headsets, interested students were asked to fill out a survey. Nine candidates were selected as they indicated a willingness to participate regularly and had different levels of VR experience. Students who did not take part in the study could participate in a video conferencing version of the course. We arranged a meeting with each participant to discuss organizational details, including information on data processing, shipping of VR headsets, and interview appointments. Before the lecture, we shipped the required hardware, a silicone hygiene cover, and a tutorial to each participant. The setup was successfully completed by all students before the first lecture.

Table 2. In-Class Activities

Cognitive Domains (Krathwohl, 2002)	Task Type	Example Task
Application	Students were asked to apply their knowledge by finding examples.	What are possibilities for using social media in companies?
Analysis	Students should compare different theories or technologies according to given criteria.	What are the similarities and differences between the given technology acceptance models?
Evaluation	Students evaluated a given topic according to strengths and weaknesses.	What are the advantages and disadvantages of (a)synchronous communication in working contexts?
Creation	Students developed strategies for specific use cases.	Develop a strategy for implementing a knowledge management tool in your company.

Research Approach

To answer our research question, we deemed the affordance network approach as most suitable, since this approach was specifically proposed for developing context-specific theories of effective use behavior (Burton-Jones & Volkoff, 2017). The five-step approach suggests depicting effective use behavior in the form of an affordance network that includes (1) characteristics of the IT artifact, (2) the ultimate goals of relevant actors, (3) actualized affordances and resulting immediate concrete outcomes, (4) dimensions of effective actualization, and (5) dependencies between the different components of the network. We selected a qualitative study design consisting of two rounds of semi-structured interviews and six sessions of participant observation to gather information regarding the network components. We applied methodological and data triangulation, meaning that we combined different qualitative research methods and collected data at two different time points (Denzin, 1989). While interviews presented the internal view of the interviewees, observations were helpful to capture unconscious or automatized behaviors (Döring & Bortz, 2016). The study was divided into two research phases (Figure 2). The first phase aimed at gaining information about the individual components of the affordance network. After an initial qualitative content analysis (Mayring, 2015), we were able to create affordance-outcome units. The second phase was used to build the affordance network by verifying the results from the initial analysis and setting the components into relation.

Research Phase 1

Before the lecture, we identified features of Spatial by testing the application and using information on the provider's website (Spatial, 2020). Furthermore, we defined the students who participated in the VR lecture as relevant actors within the scope of our study. The lecturer was not included, as she was also involved as a researcher. Further information to build the affordance network was gained by collecting qualitative data. In the first half of the semester, we conducted semi-structured interviews with all participants. Semi-structured interviews are the most frequently used interview type in information systems research and allow researchers to alter or restructure the questions during the interview, ensuring that all relevant topics are covered (Myers & Newman, 2007). Based on the required network components (Burton-Jones & Volkoff, 2017), we developed an interview guide (Table 3).

	Research Phase 1		**Research Phase 2**	
Focus	Collection of information about affordance network components		Validation of results and development of the affordance network	
Methods	Interviews, observations, qualitative content analysis		Iterative interviews, qualitative content analysis	
Results	Affordance-outcome units, dimensions of effective actualization		Affordance network	
	November 2020	December 2020	January 2021	February 2021

Figure 2. Research Approach

Table 3. Interview Guide (Phase 1)

Construct	**Example Questions**
Ultimate goals	What goals do you want to achieve in your studies? What skills or knowledge would you like to gain in the course?
Affordances and outcomes	What did Spatial enable you to do? What outcomes did you notice from using Spatial? What did [feature] enable you to do? What outcomes did you notice from using [feature]?
Dimensions of effective actualization	What do you think constitutes (in)effective use of Spatial? What do you think is the best / worst way to use Spatial in the course to achieve your goals?

After introductory questions (i.e., socio-demographics, VR experience), we questioned the students about their study goals and course-specific goals. Then, we asked the participants about affordances they actualized in Spatial and resulting outcomes using questions suggested in previous literature (Volkoff & Strong, 2013). Afterwards, we presented the list of Spatial features and asked the participants to describe the affordances and outcomes related to each feature. Lastly, we addressed effective affordance actualization, based on questions suggested by Burton-Jones & Volkoff (2017). The interviews lasted between forty and sixty minutes and were conducted via a video conferencing tool. The interviews were recorded and transcribed according to the transcription rules of Kuckartz (2018). Aiming at verifying and enriching the information gained through the interviews, we also conducted six observations of sixty to ninety minutes. A semi-structured observation with passive participation was found to be the most suitable method, as it is open minded, but contains a focus on a research question or theoretical construct (Döring & Bortz, 2016). Furthermore, the observer did not interact with the students to avoid behavioral changes (Döring & Bortz, 2016). We developed guiding questions for the observations and systematically captured notes in observation protocols (Table 4).

Nine interview transcripts and six observation protocols were included in the data analysis during the first research phase. We conducted a qualitative content analysis using a combination of deductive category formation and inductive category building (Mayring, 2015). Figure 3 illustrates the five analysis steps.

Prior to the coding, we described the research context and characteristics of the material. Then, we derived main categories based on effective use theory (i.e., ultimate goals, affordances and outcomes, dimensions of effective actualization). Furthermore, the subcategories of affordances were derived from previous literature. For each category, we added a definition based on previous literature, coding rules, and an anchor example. In the deductive coding phase, we assigned text passages from interview transcripts and observation protocols that fulfilled a category definition to the respective main category. Afterwards, we went through the coded text passages and inductively formulated subcategories for each main category. In the beginning, the level of abstraction was defined as low as possible, meaning that we formulated the categories close to the participants' statements. For each relevant text passage, we either formulated a new category or assigned the passage to an existing category. Two researchers coded the material independently from each other and discussed their understanding in several revision meetings. During the revisions, we merged similar categories, refined category names, and improved the coding guide. Once the category system remained stable, we completed the coding process using the final coding guide, as shown in the appendix. A third researcher coded 20% of the text material again using the final category system and we calculated Cohen's κ as a measure for inter-coder reliability (Cohen's κ = .83). Following Landis and Koch (1977), inter-coder reliability was interpreted as almost perfect. Based on the results, we built eight affordance-outcome units (Burton-Jones & Volkoff, 2017). We integrated all affordances into one unit that resulted in the same actualization outcome. Some affordances resulted in multiple outcomes, and thus were included in more than one unit. The units were verified and adjusted during the second research phase. There were only a few changes necessary, such as excluding one unit because the students did not perceive a major impact on goal achievement. Other units were merged, since the students identified analogies, which reduced the total number to six.

Research Phase 2

The aim of the second phase was to build the affordance network by understanding the connections between the affordance-outcome units. Therefore, we prepared an interview guide and conducted interviews with all nine students for a second time. The first interviewee received all questions as shown in Table 5 to build an initial network. In the following interviews, we verified the results and collected missing information step by step. Hence, we revised the focus of the questions after each interview, considering the existing knowledge and still required information. Nevertheless, we ensured that the students had the opportunity to verify information that was added in previously conducted interviews. Accordingly, we integrated necessary changes into the network after each interview.

Table 4. Observation Guide

Construct	Guiding Questions
Affordance actualization and outcomes	Which features are the students using? How do they use the features? Do they use additional features that were not listed in the interviews? Which outcomes result from the feature use?
Dimensions of effective actualization	Are the students using features differently? How do these differences affect the outcome?

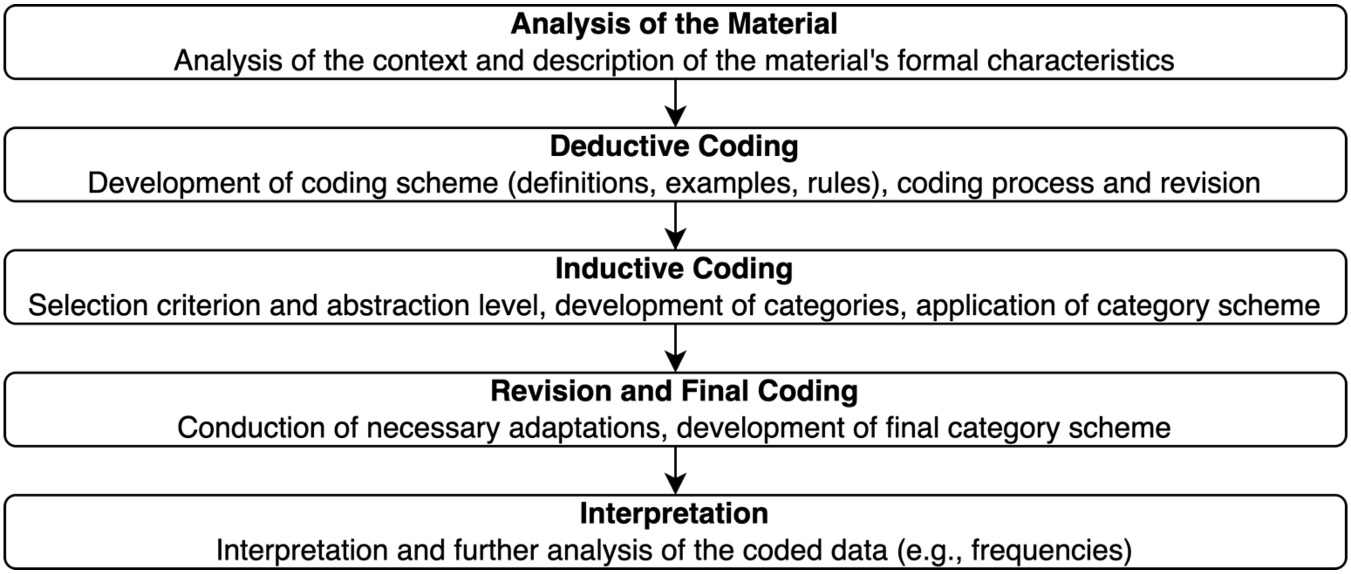


Figure 3. Qualitative Content Analysis (Based on Mayring, 2015)

Table 5. Interview Guide (Phase 2)

Construct	Example Questions
Status of goals	To what extent would you say that you have reached your goals? To what extent do you think that you have changed your goals? Did you set yourself new goals?
Affordance-outcome units	How strongly do you identify yourself with this description? Where do you see differences from your personal effective use?
Network relationships	To what extent do you see relationships between the units? What do you think is the starting point of effective use? At which point does your effective use end? Which units do you think are most important for reaching your ultimate goals?
Dimensions of effective actualization	At which point did you notice differences in the actualization of affordances? How did these differences affect the outcome?

At the beginning, we asked all interviewees about the status of their goals. Next, we presented the affordance-outcome units resulting from the first phase. The students had the chance to verify the units or suggest changes. The next section focused on the relationships between the students' goals, affordance-outcome units, and dimensions of effective actualization. In this part, we asked the participants whether they see any dependencies or sequences between the affordance-outcome units. We also asked them to provide us with additional information about the dimensions of effective actualization, such as the effect that actualization differences had on the outcomes of particular units. Mirroring the first phase, we conducted a qualitative content analysis (Mayring, 2015). The deductive category assignment resulted in the categories status of goals, affordance-outcome units, network relationships, and dimensions of effective actualization. We assigned relevant text passages to these main categories and developed inductive subcategories afterward. The final coding scheme can be found in the appendix. The second research phase resulted in a verified affordance network, depicting the effective use behavior of the students.

Results

Step 1: Nature of the IT Artefact

We identified twelve Spatial features (Table 6). The lecturer was able to select from different premade spaces allowing students to switch between rooms. Users could generate a realistic avatar including a graphical representation of their gestures. The app supported movement via teleportation. Users could upload local files (e.g., presentation slides, documents, pictures) and search the web for 3D objects and images, which could then be placed in the room. They could use the virtual keyboard, scribble feature or voice input to write sticky notes, which could be arranged on a virtual whiteboard. The Meta Quest offered a screenshot feature, built-in microphone, and headphones. This feature collection served as the basis for identifying feature-specific affordances during the interviews.

Table 6. Spatial Features

Feature	Description
Avatar	Realistic graphical representation of user appearance based on a selfie, including gestures
Teleportation	Movement within a room by selecting a target location with the controller
Reactions	Moving the controllers towards each other produces a clapping sound
3D objects	Premade scalable 3D objects, e.g., cats and cakes
Sticky notes	Color and size can be adjusted, can be labeled via drawing, typing or voice input
Scribble	Allows drawing on sticky notes or in the air
File upload	Allows uploading local files, e.g., PDF
Whiteboard	Can be used to arrange content, e.g., sticky notes
Search	Allows to search the web for additional content, e.g., images and 3D objects
Screenshots	Offered by the Meta Quest
Spaces	Premade virtual rooms (e.g., auditorium), users can switch between rooms
Audio	Users can mute or unmute themselves

Table 7. Sample Overview

Participant	Age	Gender	Semester	Level of Experience	Type of Experience
P01	22	female	5	Low	Study participation
P02	20	female	5	Low	Gaming
P03	31	female	5	High	Gaming
P04	23	female	11	Low	Gaming
P05	22	male	5	High	Work or study context
P06	27	male	11	High	Gaming
P07	24	male	6	Low	Study participation
P08	24	female	11	High	Work or study context
P09	21	female	5	None	None

Step 2: Relevant Actors and Goals

The sample consisted of nine bachelor students of cognitive and media science which is a study program consisting of information systems, computer science, and psychology courses (Table 7). Two thirds of the participants were female, one third was male. All participants have studied for at least five and up to eleven semesters. The participants were between 20 and 31 years old (*M* = 23.7). All students except one gained VR experience before the study. Four students reported little prior experience, while four students had a lot of experience. Four students have tried VR games before the study. Two students have participated in other scientific studies that involved testing VR apps. Lastly, two students have used VR as part of their work or study program.

The main goal of all students was to successfully complete the exam, because *“it opens many doors, if you have good grades”* (P03, Interview 1). Seven interviewees also wanted to improve collaboration skills and gain knowledge, such as *“how you can improve corporate communication”* (P03, Interview 1). Seven participants aimed for active and regular participation. The students had set themselves the goal of *“being there as often as possible”* (P05, Interview 1). Two students also strived for a more sustainable way of learning, resulting in better knowledge retention.

The second interviews showed that all students reached their goals indicating that they used the VR application effectively. The students stated that they gained a lot of new knowledge: *“I had a successive thread, where I could just build up my knowledge, instead of directly forgetting what was in the lecture”* (P07, Interview 2). They were able to participate in the lecture actively and regularly: *“I think, the more often I was in VR, the more comfortable I felt and the more likely I was to participate”* (P09, Interview 2). The students were also confident that they would successfully pass the exam since the in-class activities resulted in them being *“well prepared”* (P07, Interview 2).

Step 3: Affordance-Outcome Units

Overall, nine affordances emerged from the relationship of Spatial features and student users. Table 8 provides a description of each affordance and lists the features that were used for affordance actualization.

Table 8. Mapping of Spatial Features and Affordances

Affordances	Description	Features Used for Actualization
Interactivity	Students have the possibility to engage in a dialogue with each other (e.g., via audio) and react to the content of others (e.g., via avatar gestures and the clapping reaction). Users have the possibility to rate and vote for content of others (e.g., by placing 3D objects on their favorite sticky notes). Users have the possibility to manipulate sticky notes and 3D objects (e.g., moving, changing size).	Avatars, audio, reactions, sticky notes, 3D objects
Self-presentation	Students have the possibility to reveal and present information related to themselves (e.g., by customizing their avatar). This includes their name, physical appearance, and current body posture (e.g., sitting, standing, crossing arms).	Avatars
Navigability	Students have the possibility to move through the virtual environment (e.g., by teleporting), switch rooms (e.g., travel to another space to solve tasks in smaller groups) and navigate the menu.	Spaces, teleportation
Collaboration	Students have the possibility to work together toward their shared learning goals. This includes working together from distributed locations (i.e., their homes), working on joint objects (e.g., sticky notes on the whiteboard), and sharing resources (e.g., by uploading their learning materials to the virtual environment).	Whiteboard, file upload, sticky notes
Embodied cognition	Students have the possibility to feel a sense of embodiment in the virtual environment. This includes perceiving the avatar's experiences as their own.	Avatars
Relationship formation	Students have the possibility to connect with other users and build relationships with their peers (e.g., by hanging out and talking in the virtual environment before and after the course or by joking around with 3D objects).	Audio, 3D objects
Multimodality	Students have the possibility to search for information / content on the Internet (e.g., images, 3D objects) and combine it with sticky notes and scribbles.	Search, sticky notes, scribble, 3D objects
Content aggregation	Students have the possibility to organize information (e.g., by arranging sticky notes next to each other on the whiteboard) and structure information by creating topics (e.g., by using sticky notes with headlines or different colors).	Whiteboard, sticky notes
Persistence	Students have the possibility to save and archive information and content for an extended time (e.g., by taking screenshots).	Screenshots

The actualization of these affordances resulted in six outcomes. Based on the identified affordances and the associated outcomes, six affordance-outcome units were built. Table 9 provides the coding frequency of the affordances and outcomes in each unit.

Unit 1 (Increased feeling of immersion and presence): Spatial afforded *interactivity*, *self-presentation*, *navigability*, and *embodied cognition* which resulted in an *increased feeling of immersion and presence*. The avatar and reaction feature enabled interactivity with fellow students and the virtual environment. For instance, a student described: *"You can wave, you can clap, you can interact with objects. You can do with your hands what you do in the real world"* (P06, Interview 1). Moreover, the avatar feature provided the opportunity for self-presentation. For example, a student decided to customize their avatar after the second session *"so that the person in front of me finally recognizes me or can assign a face to my name. And because I do it, because the others have done it too, everyone has the result that you have a bit more of an impression that you are really together in this room"* (P08, Interview 1). Furthermore, students could *"use the teleportation feature to move around in space. As a result, you get a little bit of the feeling that, you're actually moving through a real room"* (P05, Interview 1). Lastly, the avatars afforded a sense of embodied cognition, as one student described: *"When you're standing right next to each other in Spatial, that's already unpleasant because in real life you wouldn't stand so close to each other, and you feel the need to beam yourself somewhere else. It just feels so real"* (P03, Interview 1).

Table 9. Frequency of Affordances and Outcomes

Affordances	**Units**	**Frequency**
Interactivity	1, 2, 3, 6	9/9 (100.00%)
Navigability	1, 3, 5	9/9 (100.00%)
Self-presentation	1, 2	7/9 (77.78%)
Collaboration	5, 6	9/9 (100.00%)
Embodied cognition	1	2/9 (22.22%)
Relationship formation	2	6/9 (66.67%)
Multimodality	4	8/9 (88.89%)
Content aggregation	4	8/9 (88.89%)
Persistence	6	8/9 (88.89%)
Outcomes	**Units**	**Frequency**
Increased feeling of immersion and presence	1	9/9 (100.00%)
Decreased interpersonal distance	2	9/9 (100.00%)
Increased and simplified communication	3	8/9 (88.89%)
Improved clarity of visual representations	4	8/9 (88.89%)
Improved structure and quality of collaboration	5	9/9 (100.00%)
Improved information processing and memory	6	9/9 (100.00%)

Unit 2 (Decreased interpersonal distance): The VR environment afforded *self-presentation*, *relationship formation*, and *interactivity* which led to a *decreased interpersonal distance*. It was important to actualize the self-presentation affordance by customizing one's avatar because *"I could somehow name you all that have an avatar. But I know that one or two people did not have one, but I cannot tell you their name"* (P03, Interview 1). Furthermore, students sometimes played around with 3D objects for the purpose of relationship formation which *"had the effect of breaking the ice a bit. There was definitely a big social component to it when everyone put something in the room"* (P03, Interview 1). Also, interactivity in the form of "*talking to each other is even more personal"* (P03, Interview 1). In addition, *"the avatar allows me to make gestures. And the consequences are that it also reinforces this social component because you have more of a feeling that you're not just talking to a computer"* (P05, Interview 1).

Unit 3 (Increased and simplified communication): The VR app afforded *interactivity* and *navigability* which resulted in an *increased and simplified communication*. Interactivity with each other allowed for *"a much stronger social interaction. Normally, it's not possible to stand next to each other or in front of each other, gossip, maybe pass objects back and forth, or anything else, when you're participating in a lecture from home"* (P05, Interview 1). Furthermore, navigating next to a fellow student with the teleportation feature simplified communication because students could signal to that person *"we're in a conversation right now. That really allows the social interaction to take place when you can go where you want to"* (P06, Interview 1).

Unit 4 (Improved clarity of visual representations): Spatial afforded *multimodality* as well as *content aggregation* which led to an *improved clarity of visual representations*. Students combined different types of content, for example, the students used 3D arrows and sticky notes to symbolize processes and placed their favorite objects on sticky notes to vote for ideas. Through the actualization of the multimodality affordance students could *"see at first glance: Where are the majorities? Or in which direction is the process going"* (P07, Interview 1). Furthermore, students organized and structured information, since they *"used the whiteboard to organize the sticky notes, to put them in the right order in a visually appealing and logical way. To add value from the position of each note"* (P06, Interview 1).

Unit 5 (Improved structure and quality of collaboration): The VR application afforded *navigability* and *collaboration* which resulted in an *improved structure and quality of collaboration*. Navigability facilitated group work because the teleportation feature *"has allowed me to assign myself to a group. To show, okay, I'm going to this group because we've all put ourselves in a corner"* (P05, Interview 1). Likewise, traveling to different spaces was *"great for splitting up into groups and being more undisturbed in a small group"* (P02, Interview 1). Furthermore, students used the whiteboard as a joint object for working towards a shared goal. For example, *"you can suggest something, you can pass a sticky note back and forth and say 'Hey, wouldn't this fit better?'. So just as a collaboration object, where you really come together to bring ideas together. What are the implications of that? It's just more efficient collaboration"* (P06, Interview 1). Also, the students enhanced collaboration results by preparing knowledge resources and sharing them with others in the virtual environment. A student explained, *"he had uploaded his summary of the PDF that we were supposed to read. And because we could look at it again, we could better recapitulate the topics we had to discuss in the group work"* (P04, Interview 1).

Unit 6 (Improved information processing and memory): Spatial afforded *persistence*, *collaboration*, and *interactivity* which led to *improved information processing and memory*. Students found screenshots *"super, super important, just to document and keep what happened. And also, to remember afterwards"* (P02, Interview 1). Furthermore, students believed that collaboration would enhance knowledge retention or in other words *"that the things we've worked out stick better because we've talked about them in a team, collaborated, moved things back and forth"* (P06, Interview 1). Lastly, the interactive way of information visualization helped students to better memorize information. A student explained as follows: *"This other kind of visualization that you do, well, I don't think anyone has ever created mind maps in which you pin things to the wall in 3D and can move them around. So, it's somehow a completely different way of approaching things and I think that also sticks with you longer"* (P02, Interview 1).

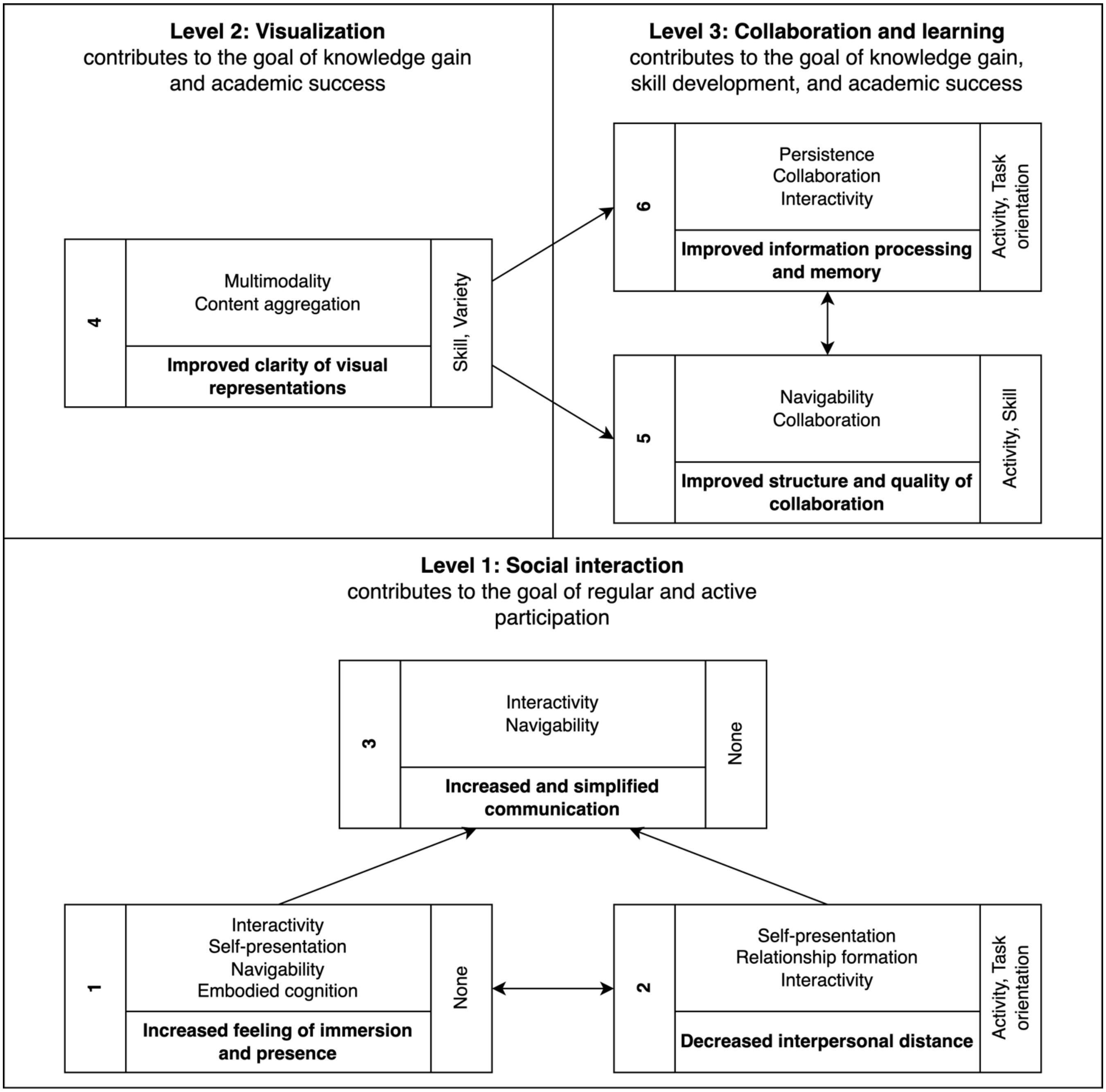
Step 4: Dimensions of Effective Actualization

While the affordance-outcome units include affordances that the students actualized as part of their effective use behavior, we found several differences in how they actualized these. In total, we identified four dimensions of effective actualization that reinforced or mitigated the outcome of specific units.

Degree of activity: Some students were more active in actualizing interactivity and collaboration, i.e., they engaged in discussions more often during group work and labeled more sticky notes with ideas. The degree of activity in actualizing these affordances had an impact on the results of affordance-outcome unit 2: *Decreased interpersonal distance*, 5: *Improved structure and quality of collaboration*, and 6: *Improved information processing and memory*. Some students *"hold back so much in communication that you actually don't hear them at all. And then it's definitely harder to build a relationship with them"* (P05, Interview 2). Furthermore, four students described that if some of them were very active, the others would stop paying attention because *"two people did the tasks and [they] could not say anything about it either"* (P03, Interview 2). Moreover, they were not able to process information if the discussion *"goes into too much detail and someone brings in very, very many aspects"* (P09, Interview 2).

Degree of skill: Observations showed that some students were less skilled in the actualization of interactivity, multimodality, and navigability. That is, they had problems in the actualization of interactivity, for example, stacking 3D objects precisely on top of each other, moving sticky notes, or labeling sticky notes in a legible way. For example, one student described "*when I took an object, and somehow moved it, I never managed to place it precisely on top of each other. And other people then put something together properly assembled"* (P02, Interview 2). In the actualization of multimodality, five students were less skilled in finding the 3D objects they imagined for combination with sticky notes. Also, in the actualization of navigability, some students were less adept at using the menu to navigate to the correct breakout room to split into smaller groups. The degree of skill in actualizing these affordances had an impact on the outcome of affordance outcome unit 4: *Improved clarity of visual representations* and 5: *Improved structure and quality of collaboration*. Unreadable sticky notes and chaotic clusters of mistakenly spawned 3D objects negatively impacted the clarity of information visualization. For example, one student explained: *"It sometimes became a bit confusing, because then all of a sudden there were objects flying around where you didn't know whether the person really wanted it and what did they mean by it"* (P03, Interview 2). Furthermore, accidentally traveling to the wrong breakout room led to more confusion at the beginning of a group work phase.

Degree of task orientation: Observations showed that some students were more or less task-oriented in the actualization of interactivity. That is, some students used 3D objects specifically to visualize task solutions, while others tended to distract from the task by merely playing around with 3D objects. As a result, the students *"needed a bit longer for everything because some people were constantly playing around with the 3D objects, because they were distracted by the play possibilities"* (P03, Interview 2). The degree of task orientation in the actualization of interactivity had an impact on the outcome of affordance-outcome unit 2: *Decreased interpersonal distance* and 6: *Improved information processing and memory*. While the task-oriented actualization of interactivity had a positive effect on information processing, the less task-oriented actualization had a distracting effect. However, a reduced interpersonal distance was perceived through joint experimentation and playing around with 3D objects. As one student puts it: *"Of course, there were also things like hey, you can make arbitrary objects appear without limitations and without anyone being able to stop you. Such things may have been more distracting than helpful in processing information. But on the other hand, it also contributed to the social feeling"* (P06, Interview 2).



* Each affordance-outcome unit is represented by a rectangle consisting of four sections. The left section represents the number of the affordance-outcome unit. The upper middle section represents the actualized affordances. The lower middle section represents the associated actualization outcomes. The right section represents the dimensions of effective actualization.

Figure 4. Affordance Network

Degree of variety: Some students were more or less variant in the actualization of content aggregation and multimodality. Observations showed that three students actualized content aggregation by, for example, coloring sticky notes differently to distinguish topics, while others adjusted the default color of sticky notes less frequently. In actualizing multimodality, three students used the scribble feature to combine handwritten explanations and drawings with the sticky notes, while others simply labeled the sticky notes briefly and concisely. The level of variety had an impact on the outcome of affordance-outcome unit 4: *Improved clarity of visual representations*. Many found the hand-labeled sticky notes and drawings less legible, however, *“if someone makes it short and concise, then it is perhaps also more plausible, i.e.,* *faster and clearer"* (P09, Interview 2). Variety in the coloring of sticky notes, on the other hand, *"has contributed to the processing of information, when you really have so many notes hanging there, which are arbitrarily colored or all in yellow, that it perhaps helps when you form colored groups"* (P04, Interview 2).

Step 5: Affordance Network

The affordance network sets the components in relation and provides a holistic understanding of the students' effective use behavior (Figure 4). All students agreed that the effective use of Spatial could not be described as a linear process. Instead, the students divided effective use behavior into three levels:

The actualization of affordances on the *first level (social interaction)* led to an increased feeling of immersion and presence, a decreased interpersonal distance as well as an increased and simplified communication. The outcomes of the units reinforced each other, for example, if the students felt immersed in the virtual environment and connected with each other, they felt *"less like in a virtual environment and more like in a real conversation"* (P05, Interview 2). Furthermore, the outcomes from unit one and two enhanced each other because if the students *"perceive a smaller distance, [their] sense of reality increases, but if [they] have an increased sense of reality, then [they] also perceive a smaller distance"* (P05, Interview 2). All students agreed on the level of social interaction as the most important foundation of their effective use.

The *second level (visualization)* includes unit four with the outcome of improved clarity of visual representations reinforcing both outcomes of the third level (collaboration and learning). Here, units five and six are integrated resulting in a more structured collaboration and improvements in information processing and memory. According to the students, a *"reasonable visual depiction"* (P05, Interview 2) led to an improved understanding and collaboration. Using 3D objects such as arrows enhanced information processing, since the students could see *"which things are connected"* (P05, Interview 2). Additionally, visual representations reinforced knowledge retention: *"I still remember the final whiteboards, what constellation they were in. Just because it was a vivid and visual capturing of the results"* (P06, Interview 2). The outcomes within the third level also reinforced each other. If the students prepared working sheets well, collaboration was perceived as more efficient as *"everyone already knew a little bit in which direction it was going"* (P05, Interview 2). This led to better information processing, also supported by the observations: Some sessions took more time, because the students were less prepared and had problems recalling their knowledge.

Each level contributed to the achievement of different goals. Three students argued that the first level supported them in active and regular participation. The social interaction was given as a reason that motivated them to participate because it was *"just something special, that [they] did not know"* (P07, Interview 2) and *"an experience that is indeed unique"* (P06, Interview 2). In contrast, five students reported that level two (visualization) and three (collaboration and learning) contributed to the goals of knowledge gain, skill development, and academic success.

Discussion

By applying the affordance network approach (Burton-Jones & Volkoff, 2017), we were able to uncover what constitutes effective use behavior regarding a VR collaboration system in digital education. While previous studies focused on two major types of information systems (i.e., reporting and planning systems), our study provides insights into effective usage behavior regarding a recording system (Burton-Jones & Volkoff, 2008). Thus, we will discuss the unique characteristics of effective use behavior with respect to different types of information systems, considering previous research and our findings.

System-Related Differences in Effective Use Behavior

First, our study provided support for nine VR affordances whose actualization contributed to the achievement of learning goals. These align with the affordances of VR and other recording systems identified in previous studies (e.g., Beach & O'Brien, 2015; Dincelli & Yayla, 2022; Treem & Leonardi, 2012; Karahanna et al., 2018; Leidner et al., 2018; O'Riordan et al., 2012; Shin et al., 2017; Suh, 2017; Steffen et al., 2019). However, especially the feature of 3D objects allowed for unique ways to actualize some affordances known from previous literature. For example, the 3D objects provided new opportunities for combining content when actualizing the multimodality affordance (Beach & O'Brien, 2015). Likewise, the relationship formation affordance is mostly known from social media studies and typically actualized using features such as friendship requests (Karahanna et al., 2018). In the VR environment in our study, however, students played around with 3D objects or handed each other random objects such as cats which sparked fun conversations, served as an icebreaker, and facilitated relationship building. Surprisingly, we found that the actualization of the relationship formation affordance also constitutes effective use behavior in digital education. Although not directly related to learning outcomes, actualization decreased the interpersonal distance facilitating communication during collaborative tasks. Nonetheless, it should also be mentioned that playing around with 3D objects, when not specifically used to actualize the multimodality or relationship formation affordances, was perceived as a distraction that prevented students from achieving their learning goals. Taken together, the identified affordances are clearly distinct from affordances found in other studies on reporting and planning systems that highlighted affordances related to data input, data retrieval, data interpretation, planning activities, and decision-making (Burton-Jones & Volkoff, 2017; Tim et al., 2020; Zeng et al., 2020; Abouzahra & Ghasemaghaei, 2022).

Second, we found four dimensions of effective actualization that enhanced or mitigated actualization outcomes. The dimension of variety is related to the dimension of consistency identified in two studies about effective use behavior regarding electronic medical record systems (Burton-Jones & Volkoff, 2017; Eden et al., 2019). We found that variety in input format (i.e., colors of sticky notes) improved the clarity of visual representations, while variety in input mode (i.e., handwriting vs. typing) had a negative effect because handwriting was harder to read. This supports findings of Eden et al. (2019) who found that overall consistency improved actualization outcomes, but in some cases, inconsistency could trigger discussions resulting in innovative work practices. The dimension of skill emerged due to the usage of VR and might be less relevant for other recording systems. For example, students were not used to searching 3D objects (low precision) and typing with controllers (low speed). However, this dimension became less relevant over time highlighting that learning about a system can improve effective use (Burton-Jones & Volkoff, 2017). The dimensions of task orientation and activity, however, could be relevant for other recording systems in collaborative contexts. For example, social networks or video conferencing tools also allow for different levels of task orientation and activity in the interaction with other users.

Third, the affordance-outcome units in our study included multiple affordances resulting in a single outcome and students did not report any strong dependencies between units (Strong et al., 2014). For example, the actualization of interactivity, self-presentation, and relationship formation often took place simultaneously and together resulted in the outcome of a decreased interpersonal distance. Also, multiple affordance-outcome units could come into play at the same time, for example, when students worked on a group task, they typically actualized affordances on all three levels. The outcomes of affordance-outcome units had enhancing effects on other units but were not a necessary condition for actualization, also called weak dependency (Strong et al., 2014). In this regard, the affordance network differs most notably from networks in other studies on reporting and planning systems. In these studies, units consisted of a single affordance resulting in a single outcome and the actualization outcome was a prerequisite for actualizing further affordances (Burton-Jones & Volkoff, 2017; Tim et al., 2020; Zeng et al., 2020; Abouzahra & Ghasemaghaei, 2022). This made the affordance network approach difficult to apply at first, but this changed as we were able to get away from the idea that effective use behavior must be a linear process in any context.

Fourth, effective use behavior in our context could be assigned to three levels that contributed to the achievement of two hierarchical goals. The three levels mirror the three dimensions of effective use (Burton-Jones & Volkoff, 2013): Actualizing affordances on the level of social interaction enabled access to representations provided by the VR application such as representations of the other students and task-related information (transparent interaction). The affordances on the level of visualization allowed the students to create visual representations of their thoughts, opinions, and task-related information (representational fidelity). The actualization of affordances on the level of collaboration and learning enabled students to process information and solve collaborative tasks based on the retrieved representations (informed action). According to Burton-Jones and Volkoff (2013), the dimensions of effective use indicate to what extent users experience effective use. This can also be seen in our network since students who only actualized affordances on the level of social interaction were limited to achieving the goal of active and regular participation. To reach the next levels of effective use, the students needed to actualize affordances on the higher levels which aligns with other studies on reporting and planning systems. For example, the actualization of increasingly advanced affordances was necessary to reach higher stages in an analytics-driven transformation (Tim et al., 2020; Zeng et al., 2020). Likewise, Abouzahra and Ghasemaghaei (2022) identified hierarchical goals of fitness wearable users and found that influencing factors hindered users at actualizing the required affordances to reach their ultimate goal of fitness improvement.

Theoretical Contribution

Our study offers four contributions to information systems research. First, we contribute a context-specific theory of effective use behavior regarding a VR collaboration system in digital education. While a quantitative study highlighted the positive influence of affordances for collaborative learning on the perceived achievement of learning goals (Jayarathna et al., 2020), our study provides a nuanced view on the relationships between individual affordance-outcome units and the impact of differences in affordance actualization.

Second, our study contributes findings on the transferability of the affordance network approach to recording systems, while prior studies focused on reporting and planning systems (Burton-Jones & Volkoff, 2017; Tim et al., 2020; Zeng et al., 2020; Abouzahra & Ghasemaghaei, 2022). We revealed differences in the affordance network providing guidance for information systems researchers. Although we focused on a VR collaboration system, we assume that the network can be adapted for other recording systems in collaborative contexts. For example, the students associated most affordances with features also offered by other recording systems such as video conferencing tools. However, VR also offers unique features such as avatars and 3D objects, and thus associated affordances such as interactivity, self-presentation, and embodied cognition might play a less important role in affordance networks related to other recording systems. Likewise, some dimensions of effective actualization might not apply to systems the users are more familiar with (i.e., skill).

Third, we contribute to a clarification of concepts surrounding effective use theory facilitating the application of the affordance network approach in information systems research. Due to the scarcity of studies applying the affordance network approach, we had difficulties in identifying how dimensions of effective use should be reflected in the network and what counts as dimensions of effective actualization. For example, Burton-Jones and Volkoff's (2017) network included *dimensions of effective actualization*, while Abouzahra and Ghasemaghaei (2022) depicted influencing factors at the same location in their network, which they in turn called *dimensions of effective use*. This arbitrary use of concepts led us to engage deeply with previous works to demonstrate a clear separation of these concepts in the application of the affordance network approach.

Fourth, we contribute insights on the interrelated affordance actualizations constituting effective use behavior based on a real class that took place in VR over the course of four months. In doing so, we expand the stream of research on VR in education, which to date has focused mainly on the assessment of learning effectiveness compared to traditional teaching in experimental studies (Dincelli & Yayla, 2022).

Practical Implications

Our research also has practical implications for educators considering the effective use of VR collaboration systems in digital education. First, educators could encourage students to actualize affordances that emerged as relevant for effective use behavior. In our course, for example, two students did not actualize the self-presentation affordance, which resulted in other students not even knowing their names by the end of the course. To promote the actualization of the self-presentation affordance and the associated outcome of a reduced interpersonal distance, educators could give the creation of a customized avatar as homework in the first session. Second, educators should define boundaries for the use of the 3D object feature. While the 3D objects can be used in a goal-oriented way to actualize relationship formation or multimodality, they were also a source of distraction. Educators should communicate clear rules such as that when somebody is talking nobody spawns a giant cat 3D object on them. To reduce distractions, it may be helpful to select a professional looking space (e.g., auditorium) for the teaching activities. Additionally, a dedicated space could be created that invites students to socialize and have fun with 3D objects before and after the lecture (e.g., roof terrace). Third, the dimensions of effective actualization provide educators with insights on how to improve the actualization outcomes. For example, educators could diminish the negative effects of low skill in affordance actualization by dedicating the first session entirely to affordance experimentation. Giving students enough time to explore affordances reduces later distractions, and students have fewer problems actualizing the interactivity, navigability, and multimodality affordances when completing tasks. From our experience, it was especially helpful for students to practice labeling sticky notes using the virtual keyboard, neatly arranging 3D objects, and precise teleportation through exercises. Furthermore, students were initially unaware that there was also a search feature, so it can help to point out more hidden features to support the exploration of affordances. Fourth, educators need to be aware of the unique characteristics of VR compared to other online teaching tools (e.g., video conferencing). For example, students cannot be automatically assigned to a breakout room with one click. However, educators could ask students to indicate their desired group membership and travel to a specific space by actualizing the navigability affordance. Furthermore, actualizing the persistence affordance required more effort than first expected. Taking screenshots of assignment results in the VR environment was difficult because handwritten sticky notes were hard to read, and students often used quite a lot of space to visualize their solution using 3D objects, scribbles, and sticky notes. Therefore, it is recommended to include a short clean-up phase after each task, where all students work together to arrange the results so that they are visible and readable on a screenshot.

Conclusion

In this study, we examined the effective use behavior with respect to a VR collaboration system in digital education applying the affordance network approach (Burton-Jones & Volkoff, 2017). We conducted 18 interviews with students who participated in a collaborative VR lecture and observations during six course sessions. Comparing our findings to previous studies enabled us to identify unique characteristics of effective use behavior regarding three major types of information systems (i.e., reporting, planning, and recording systems). We also demonstrated a clear distinction between concepts surrounding effective use theory in the application of the affordance network approach. Thus, our results contribute to a better understanding of effective use behavior and facilitate the application of the affordance network approach in the field of information systems.

Our research has some limitations highlighting areas for future research. First, we conducted our study as an initial step towards understanding affordance networks in the domain of VR in education with only a small sample size. Thus, it cannot be ensured that we reached theoretical saturation and we have been particularly careful not to draw any conclusions that do not follow from our data. Furthermore, non-response bias could have skewed our results if the participants were significantly different from those who did not participate. Second, the participants took part in a course that was graded which could have resulted in a biased dataset since students might have reported what the lecturer (i.e., one of the researchers) wanted to hear from them. Hence, future research could replicate our findings with a larger sample size in a non-biased environment. Third, we only considered effective use behavior of students and did not include the role of the lecturer in the affordance network. Future research could consider how affordance actualization of the lecturer supports or hinders students at achieving their learning goals. Fourth, we focused on the effective use of a VR collaboration system in digital education, and thus our assumptions on the transferability of the affordance network to other recording systems need to be confirmed in further studies. Although our research allowed us to draw first conclusions on differences in effective use behavior regarding other information system types, again further research is needed to generalize our findings. In addition, our research showed that variety in affordance actualization can lead to positive outcomes but can also be a hindrance. Future research is needed to investigate what degree of variety in affordance actualization contributes to the achievement of learning goals. It is conceivable that variety in affordance actualization is helpful up to a certain degree, while too much variety could lead to excessive experimentation with features or to decision paralysis in students regarding which features to use to achieve their learning goals.

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About the Authors

Jennifer Fromm is a PhD candidate at the Department of Computer Science and Applied Cognitive Science at the University of Duisburg-Essen, Germany. She received a master's degree in Applied Cognitive and Media Science from the University of Duisburg-Essen, Germany. Her studies focus on the effective use of virtual and augmented reality in application areas such as crisis management and higher education. Her research has been published in journals such as *Information Systems Frontiers*, *Computers & Education* and *The Internet and Higher Education*.

Stefan Stieglitz is professor and head of the Chair for Business Information Systems and Digital Transformation (SAP-endowed) at the University of Potsdam, Germany. In his research, he investigates how to make use of social media data. Moreover, he analyzes user behavior and technology adoption of collaborative information systems in organizational contexts. He is director and founder of the Competence Center Connected Organization. Stefan has been an honorary professor at University of Sydney since 2018. His work has been published in reputable journals such as the *Journal of Management Information Systems*, *European Journal of Information Systems*, *Journal of Information Technology*, and *Business & Information Systems Engineering*. One of his articles was awarded with the 'Stafford Beer Medal' for the best paper in the *European Journal of Information Systems* in 2019. Furthermore, one of his articles was recognized with the 'AIS Senior Scholars Best IS Publications Award' in 2016.

Milad Mirbabaie is junior professor for information systems at Paderborn University, Germany. Prior to this position, he was interim professor for information systems at the University of Bremen and team leader and post-doc for sociotechnical systems at the University of Duisburg-Essen, Germany. He studied Information Systems at the University of Hamburg and received his PhD from the University of Münster, Germany. He has published in reputable journals such as *Internet Research*, *Information Systems Frontiers*, *International Journal of Information Management,* and *International Journal of Human Computer Interaction*. His work focuses on socio-technical systems, artificial intelligence, social media, digital work, and crisis management. In 2017, one of his articles was awarded with the 'Claudio Ciborra Award' at the *European Conference on Information Systems* for the most innovative research article.

Appendix

Table A.1. Coding Guide (Research Phase 1)

Subcategory	Definition and Coding Rules	Anchor Example
Ultimate goals: Includes all statements about the students' goals. Does not include goals that have already been reached or goals which are not related to their general study or the specific lecture.		
Academic success	Includes all goals that are related to successful events in the context of the participants' study, such as passing final exams.	*"And at the end, I want a grade that I am satisfied with." (P09, Interview 1)*
Development and improvement of skills	Includes all statements in which the participants mention that they would like to develop new or improve existing hard or soft skills, e.g., collaboration skills. Does not include the gathering of theoretical knowledge.	*"(…) to work with other people. For example, in school it was difficult for me to work with other people, simply because it was also relatively rare." (P01, Interview 1)*
Knowledge gain	Describes all goals that focus on attaining general knowledge as well as knowledge regarding specific theoretical constructs. Does not include the development of practical skills.	*"(…) how communication takes place in a sensible way, how you can improve communication also in the professional context." (P03, Interview 1)*
Regular and active participation in the lecture	Contains passages in which the participants describe that they would like to participate in the lecture with a high frequency as well as contribute to the lecture with high quality. Includes for example statements about reaching valuable results in group works.	*"Well, to solve the task as comprehensively and as well as possible in the end, whatever task we got." (P05, Interview 1)*
Improved learning behavior	Includes all statements in which the students describe desired changes in their learning patterns, for example by altering the frequency, sustainability, type or point in time of learning.	*"(…) that I learn a bit more sustainably and remember things better." (P02, Interview 1)*
Affordances: Includes all descriptions of Spatial's affordances, meaning what the technology enabled the students to do. Does not include affordances of other virtual reality applications. Does not include technology features or results from affordance actualization.		
Interactivity (Beach & O'Brien, 2015; Boy et al., 2016; Patwardhan & Murthy, 2015; Karahanna et al., 2018; Steffen et al., 2019; Zhou et al., 2021; Dincelli & Yayla, 2022)	Students have the possibility to engage in a dialogue with each other (e.g., via audio) and react to the content of others (e.g., via avatar gestures and the clapping reaction). Users have the possibility to rate and vote for content of others (e.g., by placing 3D objects on their favorite sticky notes). Users have the possibility to manipulate sticky notes and 3D objects (e.g., moving, changing size).	*"This feature allows you to move things around in space. So, if you have objects, you can make them bigger, make them smaller." (P04, Interview 1)*
Self-presentation (Suh, 2017; Karahanna et al., 2018)	Students have the possibility to reveal and present information related to themselves (e.g., by customizing their avatar). This includes their name, physical appearance,	*"I use the avatar to show the people in the room what I look like." (P05, Interview 1)*

	and current body posture (e.g., sitting, standing, crossing arms).	
Navigability (Zhou et al., 2021; Dincelli & Yayla, 2022)	Students have the possibility to move through the virtual environment (e.g., by teleporting), switch rooms (e.g., travel to another space to solve tasks in smaller groups) and navigate the menu.	*"I use the feature to move around the room. But it has also enabled me, for example, to assign myself to a group when we were divided into group work. To show, okay, I'm going to this group because we all stood in the same corner." (P05, Interview 1)*
Collaboration (Beach & O'Brien, 2015; Steffen et al., 2019; Karahanna et al., 2018)	Students have the possibility to work together toward their shared learning goals. This includes working together from distributed locations (i.e., their homes), working on joint objects (e.g., sticky notes on the whiteboard), and sharing resources (e.g., by uploading their learning materials to the virtual environment).	*"We often use sticky notes to solve tasks with others." (P09, Interview 1)*
Embodied cognition (Shin et al., 2017)	Students have the possibility to feel a sense of embodiment in the virtual environment. This includes perceiving the avatar's experiences as their own.	*"Well, I didn't think before that it would feel so real as if you had just met with people. I also find that when you stand right next to each other in Spatial, it's already unpleasant, because in real life you wouldn't stand so close to each other, and you already feel the need to beam yourself somewhere else." (P03, Interview 1)*
Relationship formation (Karahanna et al., 2018; Leidner et al., 2018)	Students have the possibility to connect with other users and build relationships with their peers (e.g., by hanging out and talking in the virtual environment before and after the course or by joking around with 3D objects).	*"Right now, I can only think of fun activities that somehow loosen up the whole thing. And I also think that at the very beginning, when we were all in the room for the very first time, we used them to try things out a bit. And I even think that the objects had the effect of breaking the ice a bit. At least that's how I perceived it. There was definitely a big social component to it when everyone put something in the room."* (P08, Interview 1)
Multimodality (Beach & O'Brien, 2015)	Students have the possibility to search for information / content on the Internet (e.g., images, 3D objects) and combine it with sticky notes and scribbles.	*"I use the feature to make different things clear in the collaboration either to make a process clear with the arrow or we have already used it to make polls, expressions of opinions or ratings clear."* (P07, Interview 1)
Content aggregation (O'Riordan et al., 2012)	Students have the possibility to organize information (e.g., by arranging sticky notes next to each other on the whiteboard) and structure information by creating topics (e.g., by using sticky notes with headlines or different colors).	*"I can write down my ideas, either in text format or by hand, and can visually place that information in a room and can classify them through the place where I put the sticky note."* (P06, Interview 1)
Persistence (Treem & Leonardi, 2012; Karahanna et al., 2018)	Students have the possibility to save and archive information and content for an extended time (e.g., by taking screenshots).	*"(…) capturing things is probably the most important thing. So, contents on the whiteboard for example.*

		Things that you may need for later group work. Things that you maybe want to look at again to deepen your understanding. All this can be screenshotted. Of course, you can also screenshot if there are funny things somewhere." (P05, Interview 1)
Immediate concrete outcomes: Includes all depictions of changes that resulted from the actualization of affordances provided by Spatial, such as changes in the participants' feelings or improvements of their interaction. Does not include descriptions of action potentials, but only the results of actualization.		
Increased feeling of immersion and presence	Contains all statements in which the interviewees describe that they feel like really being together in a room with the other students. Additionally, includes statements describing an enhanced level of immersion in the virtual environment.	*"It just makes the whole thing a little bit more real. So, I mean, the bottom line is that you're sitting at your desk at home, but by being in this room, it's just a realistic action."* (P04, Interview 1)
Decreased interpersonal distance	The interaction between the students has been perceived as more personal and less distanced. Includes for example statements in which the participants mention that they have increasingly bonded with the other students. Does not include statements depicting an easier or increased communication because this category focuses more on the relationship between the users.	*"I like them all, but I directly had a personal relationship with the people, who had an avatar. Some do not have one. I think I could somehow name you all, that have an avatar. But I know that around one or two people did not have one, but I cannot tell you their name, because I was not able to memorize them because of that." (P03, Interview 1)*
Increased and simplified communication	Contains all passages which describe positive changes in the interaction between the students, mainly referring to an increased intensity and easiness of the communication. Includes for example descriptions of more active discussions. Does not include statements describing the outcome of a more personal communication.	*"So, I think that communication is more simplified, then if you would only have a chat. You can just express yourself better if you are talking to each other." (P04, Interview 1)*
Improved clarity of visual representations	Includes passages in which the students state that information is presented more clearly, meaning that they are more structured, and relations are visible at a first glance.	*"Better perception of correlations. Better overview for me." (P07, Interview 1)*
Improved structure and quality of collaboration	Contains passages depicting that the collaboration between students is more effective. This includes, for example, that it is more structured or easier or that the result of the collaboration is of higher quality.	"So, that it is more structured, that you are not distracting each other, that you can work concentrated and quietly first." (P03, Interview 1)
Improved information processing and memory	The interviewees process and retain information better. In more detail, they understand, learn, and remember the knowledge better. Hence, this category includes, for example, statements regarding an increasing learning effect, a better memory or easier understanding of the learning contents.	*"I can find my way back into situations more easily. I have a better memory of the current situation, of what happened." (P07, Interview 1)*
Dimensions of effective actualization: Includes statements on differences in the actualization of affordances. Does not include external factors hindering or facilitating the actualization itself.		
Degree of activity	Refers to differences in frequency	*"P07 takes a leading role in the*

	and intensity of affordance actualization. Includes statements describing that some students were more reluctant to actualize affordances (e.g., engaged in discussions less often), while others actualized the same affordance frequently (e.g., often took a leading role in discussions).	*discussion in the second task, as he often asks questions to the others or comments on their suggestions."* (Observation 06)
Degree of skill	Refers to differences in skill in actualizing affordances that are due to low experience using the technology. Includes statements describing that some students made more errors in actualization (e.g., accidentally navigating to the wrong breakout room) or took significantly longer to actualize affordances with satisfactory results (e.g., labeling sticky notes legibly), while others actualized affordances with more ease.	*"P09 accidentally deletes a note and then creates a new one." (Observation 05)*
Degree of task orientation	Refers to differences in task orientation in the actualization of affordances. Includes statements describing that some students actualized affordances with reference to the task (e.g., using 3D objects to visualize connections between concepts), while others actualized the same affordance for entertaining reasons without contributing to the solution of the task (e.g., playing around with 3D objects).	*"P06 tries the search for 3D objects, for example he inserts a bird object while the others discuss the task." (Observation 05)*
Degree of variety	Refers to differences in variety in the actualization of affordances. Includes statements describing that some students actualized the same affordance multiple times in different ways (e.g., coloring the background color of sticky notes differently to better distinguish topics), while others always actualized the same affordance in the same way (e.g., always attaching sticky notes to the whiteboard in the same color).	*"In between, P02 and P08 adjust the colors of the sticky notes again and again, while the others only use the standard color of the sticky notes." (Observation 05)*

Table A.2. Coding Guide (Research Phase 2)

Subcategory	Definition and Coding Rules	Anchor Example
Status of goals: In this category, all statements that give an update about the students' goals are included. Hence, this main category mainly aims at portraying changes during the research process.		
Goal attainment	Contains all statements in which the interviewees describe to what extent they have reached their ultimate goals.	*"As far as active participation is concerned, I think, the more often I was in VR, the more comfortable I felt and the more likely I was to participate. I think it was always easier when the group was smaller. Yes, I think overall I have already achieved the goals." (P09, Interview 2)*
Goal adjustments	Refers to all passages in which the students depict changes in their goals compared to the goals that have been mentioned in the first interview. Includes for example changes in their priorities or the emergence of new goals.	*"But I have to say that it is less important to me that I somehow pass the exam well or very well. I think that has changed a bit for me." (P08, Interview 2)*
Affordance-outcome units: Includes statements the students have made after the affordance- outcome units were presented. This category is mainly used to perform necessary adjustments in the units to develop an affordance network which describes the students' effective use best possible.		
Verification statements	Contains all statements in which the students confirmed that the affordance-outcome units depict their effective use behavior.	*"Yes, I would definitely agree that entertaining activities reduced the distance between us."* (P06, Interview 2)
Necessary adjustments	Contains all statements that were used to adjust the affordance- outcome units. This means that all statements are coded in which the students describe alternative suggestions to the version of the network presented by the interviewer.	*"Maybe that would be something, which could be added. The collective experience in the room." (P08, Interview 2)*
Network relationships: In this category, all passages in which the students do not only talk about the affordance-outcome units, but rather how they relate to each other, are coded. Hence, this category is used to portray the interaction of the different units.		
Verification statements	Contains all statements in which the students confirmed the relationships between units that were suggested in previous interviews.	*"Yes, I would also say that the level of social interaction is the foundation of everything else."* (P06, Interview 2)
Necessary adjustments	Contains all statements that were used to adjust the relationships between the affordance-outcome units. This means that all statements are coded in which the students describe alternative suggestions to the version of the network presented by the interviewer.	*"I am not a hundred percent sure whether the increased readability provides an extreme added value." (P06, Interview 2)*
Dependencies and sequences	In this category, all passages were coded, in which the students depict dependencies or sequences in the affordance network. In more detail, this would for example include if one affordance-outcome unit enables another.	*"So, I would just say that the uppermost [level 1] is the basic requirement and therefore, the lower processes arise in the first place, where they are. So, that social exchange is their basis."* (P07, Interview 2)
Relevance for goal attainment	Refers to all statements in which the students mention how the different affordance-outcome units supported them in reaching their ultimate goals. Does not include statements in which they describe to what extent they have reached their	*"I think the things that actually contribute to the goals that I had now, that would be I think the two [units] from the collaboration and learning level, so level 3, simply because I think a structured and efficient collaboration and of course a better memory and information*

	goals overall, without referring to specific affordances or outcomes.	*processing also helps you learn better and learn more effectively and maybe also notice better that you deal with things more regularly." (P05, Interview 2)*
Dimensions of effective actualization: Includes statements in which the interviewees mention differences in affordance actualization, since insights regarding this component of the network were mainly gained through observations during the first research phase. Does not include external factors hindering or facilitating the actualization itself.		
Degree of activity	For a general definition of the categories, see Table A.1. Moreover, in the second phase, not only differences in actualization were coded, but also their effect on actualization outcomes. This could include for example segments, in which the students describe that the active, skillful, task-oriented, or varied actualization of an affordance further reinforced its outcome.	*"There are also people who hold back so much in communication that you actually do not hear them at all. And then it's definitely harder to build a relationship with them."* (P05, Interview 2)
Degree of skill		*"I also noticed that some people had problems finding objects in the first place. And then the objects flew around the room. And other people immediately found the objects they wanted and used them." (P03, Interview 2)*
Degree of task orientation		*"Of course, there were also things like hey, you can make arbitrary objects appear without limitations and without anyone being able to stop you. Such things may have been more distracting than helpful in processing information. But on the other hand, it also contributed to the social feeling" (P06, Interview 2).*
Degree of variety		*"I was also a big fan of the colored sticky notes. I think it has contributed to the processing of information, when you really have so many notes hanging there, which are arbitrarily colored or all in yellow, that it perhaps helps when you form colored groups" (P04, Interview 2).*

The Effects of Virtual Reality Affordances and Constraints on Negative Group Effects during Brainstorming Sessions

Jennifer Fromm[1], Milad Mirbabaie[2], and Stefan Stieglitz[1]

[1] University of Duisburg-Essen, Professional Communication in Electronic Media / Social Media, Duisburg, Germany
jennifer.fromm@uni-due.de, stefan.stieglitz@uni-due.de
[2] University of Bremen, Information Systems and Industrial Services, Bremen, Germany
milad.mirbabaie@uni-bremen.de

Abstract. Idea generation processes are important for companies to develop new products and services, and brainstorming is a popular method for generating ideas in groups. However, it has been shown that negative group effects can occur during brainstorming sessions, especially since teams today often collaborate from different locations. Therefore, electronic brainstorming systems are needed that foster creativity while reducing negative group effects. We extend the research on electronic brainstorming systems by investigating how virtual reality affordances and constraints influence the occurrence of negative group effects in virtual reality brainstorming sessions. We conduct a qualitative study with 18 participants consisting of virtual reality brainstorming sessions and subsequent interviews. Using the affordance network approach, we explain the occurrence of production blocking and evaluation apprehension. Furthermore, we suggest extending this approach by incorporating constraint-outcome units and discuss whether the notion of affordance actualization can be transferred to constraints.

Keywords: Affordances, Constraints, Virtual Reality, Negative Group Effects, Brainstorming

1 Introduction

Developing new products and services is important for companies to remain competitive, and the development of innovative products and services is based on a company's ability to come up with new ideas [1]. To develop solutions for increasingly complex problems, today's companies usually work in interdisciplinary teams. Furthermore, the internet enables geographically dispersed teams to work together [2]. This makes it possible to include the perspectives of employees and customers from all over the world in idea generation processes. However, it is also a challenge to design systems that promote creative thinking and enable teams to remotely work together [3].

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Brainstorming is a frequently used method for collaborative idea generation, but several studies revealed that under certain circumstances individuals perform better brainstorming separately than in groups [4–6]. The reason is the occurrence of negative group effects, such as production blocking, evaluation apprehension, social comparisons, cognitive inertia, and social loafing [7]. Previous research has shown that electronic brainstorming systems (EBS) such as chats or discussion forums increase the brainstorming performance of groups [8, 9]. In particular, production blocking and evaluation apprehension can be counteracted by the simultaneous input of ideas and a high degree of anonymity [9, 10]. However, the occurrence of other effects such as social loafing is more likely due to the high degree of anonymity [11]. Thus, it is relevant to examine which other technologies have a creativity-promoting effect and at the same time prevent the occurrence of negative group effects. In this article, we focus on virtual reality (VR) as a technology that has evolved in recent times and is considered to have high creativity-promoting potential. In this regard, Alahuhta et al. [12] identified eight creativity-promoting affordances of VR: 1) avatars as graphic self-representations, 2) changing the users' frame of reference, 3) co-presence, 4) immersion, 5) multi-modality, 6) rich visual information, 7) simulation capabilities, and 8) supporting tools for creative work [12]. However, the question of how VR influences the emergence of negative group effects in idea generation processes has received less attention so far. We therefore draw on the concepts of technology affordances and constraints [13] to answer the following research question:

RQ: *How do VR affordances and constraints influence the occurrence of negative group effects in VR brainstorming sessions?*

In the next section, we provide the theoretical background on brainstorming and negative group effects. Then, we discuss the creativity-promoting affordances of VR and introduce the concepts of technology affordances and constraints [13]. Afterwards, we describe our qualitative research design consisting of VR brainstorming sessions and interviews. We then report on the interview results and discuss how VR affordances and constraints affect negative group effects in idea generation processes. Furthermore, we show limitations of our study and possibilities for future research.

2 Theoretical Background

2.1 Brainstorming and Negative Group Effects

Brainstorming is a method for idea generation that is intended to promote the development of new, unusual ideas in a group of people [14]. The basic assumption is that people are able to develop more ideas in a group than on their own, and the following four rules were proposed to maximize the output of brainstorming sessions: 1. the more ideas, the better, 2. the more unusual the ideas, the better, 3. improve and add to ideas already mentioned, and 4. abstain from any criticism [14]. Research has shown that groups following these principles perform better than those that do not

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[15]. However, it has also been repeatedly shown that the combined individuals' performance is better than the group's performance when it comes to brainstorming [4–6]. One explanation for the poorer performance in brainstorming groups is the occurrence of negative group effects.

Negative group effects can be distinguished by procedural, sociopsychological, and economic mechanisms [6]. *Production blocking* is a procedural mechanism and arises when one's own flow of thoughts is interrupted while one listens to other group members expressing their ideas [5]. *Evaluation apprehension* is a sociopsychological mechanism that means group members do not express their own ideas for fear of negative evaluation by other participants [16]. *Social comparisons* also belong to the category of sociopsychological mechanisms and refer to a comparison of one's own brainstorming performance with the performance of other group members [17]. Upward comparisons can increase performance, since group members can be motivated to improve their own performance by the higher performance of others [7]. However, downward comparisons may lead to a decrease in group performance, as high performers may feel deviant and want to conceal their successful efforts [7]. Another sociopsychological mechanism is *cognitive inertia*, which means following the opinions of others, as it is psychologically more comfortable than contradicting opinions or initiating a change of topic [18]. *Social loafing* is an economical mechanism and can be defined as the decrease in individual effort due to the social presence of others [19]. This effect occurs in particular when the individual performance of the group members cannot be clearly identified and the individual group members cannot be held accountable [11].

Using computer-based programs for group brainstorming is one way to counteract negative group effects. It has been shown that groups generate more ideas in EBS than individuals do [8, 9]. The main reason cited for this was the elimination of production blocking [9]. In EBS, participants write down their ideas in a chat or discussion forum [20]. In this way, participants can express ideas at the same time and are no longer blocked in their flow of thoughts by others speaking. EBS also ensure a high degree of anonymity, which can favor social loafing since the contributions can no longer be clearly assigned to individual group members [11]. However, the high degree of anonymity can also mitigate the effect of evaluation apprehension [10].

2.2 Creativity-Promoting Affordances of Virtual Reality

In this article, we focus on VR, which can be defined as "the sum of the hardware and software systems that seek to perfect an all-inclusive, immersive, sensory illusion of being present in another environment" [21]. It is assumed that VR has high potential to promote creativity. For example, Bhagwatwar et al. [22] found that groups generated more ideas in a creative-priming VR environment than groups in an environment that looked like a standard office space. A systematic literature review further identified eight creativity-fostering affordances of VR environments. Avatars play a central role because they allow users to present themselves differently than in the real world. In this context, it has already been discovered that avatars that made group members look like inventors led to increased brainstorming performance [23].

In addition, avatars allow participants to express their ideas verbally and non-verbally, fostering creative interaction [24]. Moreover, avatars can be perceived as a protective shield that allows users to feel comfortable and safe while expressing their ideas [25]. The virtual environment also offers high creative potential because it can be adapted to the creative task to provide additional inspiration [26]. At the same time, users can express their ideas not only verbally, but also visually in the form of 3D objects or 3D drawings. VR affords the creation of virtual objects that would be inconceivable in the real world, promoting the challenging of conventions and presumptions [27]. Through a high degree of immersion, users experience co-presence. The feeling of being present in a shared space can increase participation in an idea generation session [28]. The high degree of immersion can also lead to a stronger focus on the current activities within the virtual environment, as events in the real world are not perceived to the same degree [22].

The affordance concept originated in ecological psychology and describes how different species perceive the action potential of their environment [29]. The concept was adapted in the field of Information Systems to investigate the effects of technologies on individuals, groups, and organizations [30]. Majchrzak and Markus [13] distinguish between technology affordance, which describes *"what an individual or organization with a particular purpose can do with a technology or information system,"* and technology constraint, which *"refers to ways in which an individual or organization can be held back from accomplishing a particular goal when using a technology or system."* It is important to distinguish that affordances and constraints are not the same as technology features, but potentials and constraints for actions, which is why affordances and constraints are best described using verbs [13]. Nevertheless, the design of technologies can influence which affordances and constraints are perceived by users [31]. Once users perceive affordances, they can perform various actions to realize their potential, which is called affordance actualization [32]. The actualization of affordances results in immediate concrete outcomes which in turn can result in the emergence of new affordances [33]. In this regard, Burton-Jones and Volkoff [34] propose affordance-outcome units as building blocks of affordance networks that map the connections and feedback loops between different affordance-outcome units. In our research, we used this approach to understand how VR affordances and constraints are linked to negative group effects during brainstorming sessions.

3 Research Design

3.1 Sample and Procedure

In order to investigate how VR affordances and constraints influence the occurrence of negative group effects, we conducted a qualitative study. The study consisted of a VR brainstorming session followed by interviews with the participants. These were recruited in the Applied Cognitive and Media Sciences study program through Facebook advertising. A total of 18 students with brainstorming experience

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participated, with the sample consisting of nine females and nine males. On average, the participants were 22.5 years old, with the youngest being 20 years and the oldest 26 years old. All participants brainstormed regularly as part of university courses or their part-time jobs but had no theoretical knowledge about negative group effects. Due to the focus on media studies, students from the above-mentioned program usually have a high interest in trying out new media including VR. Therefore, all participants had tried VR at least once before the study (e.g. played a VR game in their free time).

3.2 Brainstorming Session

We conducted six VR brainstorming sessions with three participants each. The subgroups were formed based on the participants' availability dates, which were queried by a Doodle survey prior to the study. In our study, we aimed to realistically simulate the use of VR for brainstorming in a geographically dispersed team. To simulate remote idea generation processes, the participants took part from their homes and were therefore not at the same location. To further increase the degree of realism, we decided to use the Oculus Go as a portable headset that does not require any additional hardware to run. This way, team members could participate from their usual workspace, from home or even from a hotel room on a business trip. However, to the best of our knowledge, there does not exist a dedicated brainstorming application for this device, yet. Most VR applications with dedicated brainstorming functionalities (e.g. Glue) are only available for VR headsets that require a high-performance computer and tracking stations to run. We did not consider it realistic for all employees in geographically dispersed teams to have such hardware available at all times. Therefore, we decided to use the existing social network application vTime XR [35] that is available for the Oculus Go.

vTime XR allows users to create a private room and communicate with each other. The application offers different environments, from an underwater city to a floating space station. In our study, we selected the library environment because we considered it to be the place where students in the real world would most likely meet for a brainstorming session. In the library, the participants sat around a rectangular table as shown in Figure 1. The surroundings contained numerous details such as a crackling fire or a meowing cat. The application did not provide visualization features such as a shared whiteboard. The participants were represented by avatars that we created as close as possible to the actual appearances of the participants before the study.

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Figure 1. The library environment in vTime XR

The Oculus Go is an all-in-one headset that requires no external hardware or tracking stations. In addition to built-in speakers, the device has a microphone that allows real time communication with other participants. The sensors in the Oculus Go detect rotating movements of the head, namely rolling, pitching, and yawing (3DOF), but do not support tracking of the user's position in the room. The included controller acts as a pointer and allows the user to interact with menus and virtual objects. Due to the tracking limitations, it is not possible in vTime XR to transfer the actual facial expressions and gestures of the user. Instead, the avatar of the currently speaking person automatically shows pre-programmed facial expressions and gestures. Before the session started, we introduced the participants to each other because they did not know each other before. We further explained the basic principles of brainstorming. Afterward, we asked the participants to collect as many ideas as possible for increasing the voter turnout of young people within 12 minutes. The topic was chosen because it had personal relevance for the participants as eligible voters in view of the upcoming European elections. As the participants themselves were among the group of young voters, we assumed that every participant should be able to express ideas on this topic. During the brainstorming session, we left the room and the session was not recorded so that negative group effects would not occur because the participants felt observed.

3.3 Interview

Immediately after the brainstorming session, the participants were interviewed simultaneously at home by one of three interviewers. Before the start of the study, we prepared an interview guide, but additional questions were asked during the interview. At the beginning of the interview, we asked the participants to summarize the results of their group and describe their impressions of the brainstorming session. This was followed by the main part of the interview, in which the participants indicated to what extent they perceived negative group effects. Participants were also asked about the reasons for the (non-)occurrence of these effects.

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1. **Production blocking:** Participants were asked how they assessed their speaking time and that of their group members. They were also asked what they were thinking about while others were expressing their ideas.
2. **Evaluation apprehension:** Participants were asked to assess their knowledge on the brainstorming topic and that of their group members. They were also asked how they felt about expressing their ideas and whether there were cases where they did not express their ideas.
3. **Social comparison:** Participants were asked to assess their performance against the performance of their group members. They were also asked what thoughts they had about the performance of their group during the brainstorming session and how they adapted their behavior based on these thoughts.
4. **Cognitive inertia:** Participants were asked if they had allowed themselves to be distracted from their own opinions. They were also asked if they agreed with the ideas of the other participants, even though they were not persuaded by them.
5. **Social loafing:** Participants were asked to assess their efforts and those of their group members. Participants were also asked how it would have affected the group results if they had not been involved in the brainstorming session.

In the final part of the interview, the participants were asked about their previous brainstorming and VR experiences. They were also asked to report differences between the VR brainstorming session and previous brainstorming experiences. The interview ended with the collection of sociodemographic data. In total, the interviews lasted between 15 and 35 minutes. In preparation for the analysis, the interviews were recorded and transcribed according to the rules of Kuckartz [36].

3.4 Qualitative Content Analysis

To analyze the interviews, we combined the deductive approach with the inductive approach of category formation according to Mayring [37]. Based on our research question and the theoretical background, we identified *technology characteristics*, *affordances* and *constraints, immediate concrete outcomes* and *negative group effects* as main categories. For the last main category, we also deductively created the following negative group effects as subcategories: *production blocking*, *evaluation apprehension*, *social comparison*, *cognitive inertia,* and *social loafing*. For the other main categories, we inductively formed corresponding subcategories. Two researchers coded the interviews and discussed inconsistencies until they reached agreement. To analyze how VR affordances and constraints influence the occurrence of negative group effects, we used the affordance network approach of Burton-Jones and Volkoff [34]. Based on the interview statements of the participants, we linked affordances and constraints with VR technology characteristics and immediate concrete outcomes. By doing so, we were able to retroduce how the affordances and constraints of the used VR technology influenced the occurrence of negative group effects.

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4 Results

4.1 Virtual Reality Affordances and Constraints

Overall, the participants perceived a variety of VR affordances and constraints during their brainstorming sessions. The actualization of these affordances and constraints resulted in different immediate concrete outcomes of which some manifested in negative group effects. Note that affordances are not always positive, and constraints are not always negative. As will become clear later, both affordances and constraints could be associated with negative group effects. Table 1 provides a mapping of the technology characteristics, affordances, constraints, and immediate concrete outcomes.

Table 1. Mapping of Technology Characteristics, Affordances, Constraints, and Immediate Concrete Outcomes

Technology Characteristics	*Affordances and Constraints*	*Immediate Concrete Outcomes*
Head-mounted display	A: Immersing oneself in the virtual environment	Increased focus on the task
3DOF	A: Looking at each other	More natural conversation
Pointer controller Pre-programmed facial expressions / gestures	C: Expressing oneself through facial expressions and gestures	More natural conversation Increased difficulty to underline one's arguments Increased difficulty to receive the others' attention Increased difficulty to recognize when others speak Increased uncertainty about the others' reaction
Delays	A: Communicating respectfully	Increased attention Increased waiting time
Avatars	A: Changing one's appearance	More natural conversation Relaxed atmosphere Increased thinking in stereotypes
Rich virtual environment	A: Discussing about details in the environment	Distraction from the task Relaxed atmosphere
Seating arrangement	C: Looking at each other	Increased difficulty to recognize when others speak Increased difficulty to receive the others' attention
Lack of visualization tools	C: Visualizing ideas	Difficulties to tie in with the ideas of others (third brainstorming rule)

The head-mounted display allowed the participants to immerse themselves in the virtual environment and as a result five participants focused more on the brainstorming task (A1, B1, C1, F12). One participant expressed that he *"was much more invested than if he just looked at a screen* (C1)*."* Overall, most participants were pleasantly surprised by the VR experience and four participants described it as very relaxing (A2, C1, F12). The relaxed atmosphere emerged because the participants did not have to worry about their appearance as they were represented by an avatar. One participant even imagined: *"I would no longer have to go to work but could sit at home and wear sweatpants or none at all* (C1)*."* However, the opportunity to change one's appearance also fostered stereotypical thinking as one participant described that *"the person with the glasses looked much more intellectual and professional* (B2)*."* The design of the virtual environment afforded discussions about details in the environment which further contributed to the relaxed atmosphere but also resulted in a distraction from the brainstorming task (A23, B123, C13, D1, E12, F13). In this regard, one participant described that *"there was a lot going on in the room and there was a lot to see. I think it was a bit rude of me to look at the cat, the fire, the pictures on the wall or the books under the table. These things were much more interesting than the people* (B3)*."* To limit the distractions, three participants would have preferred a simpler environment, such as a meeting room (B3, E2, F3). The lack of note-taking tools constrained the visualization of ideas which is why most participants perceived it as more difficult to tie in with the ideas of others (A3, B13, C12, D13, E2, F23).

Overall, one third of the participants perceived the interaction as more natural than expected (C1, E23, F123). One participant even described the interaction as *"about as good as if you were sitting in a room talking* (C1)*."* The impression of a natural interaction was created by the representation as avatars, the possibility to look at each other and the pre-programmed facial expressions and gestures. While the head-mounted display afforded the activity of looking at each other, the fixed seating arrangement in the virtual environment constrained this activity at the same time. Two participants were sitting directly opposite each other and perceived the interaction as very natural. However, the distance to the remaining participant was much larger, and therefore they often did not recognize when he or she started to speak. As a result, participants in all groups described a lively exchange of ideas between two participants while the remaining one had difficulties receiving the others' attention (A2, B2, C13, D13, E1, F23).

Furthermore, many participants expected their actual facial expressions and gestures to be transferred into the virtual environment. However, the avatars in vTime XR show only pre-programmed facial expressions and gestures to signal who is speaking which constrained the participants in expressing themselves. For most participants, this was disturbing and confusing (A1, B123, C123, D123, E123, F13), as one participant described, *"I always gestured wildly, and it was weird that I could not see that on my avatar* (B3)*."* Another participant experienced the opposite—while he used very few gestures, he could see how his avatar was gesticulating wildly (C2). On the one hand, the pre-programmed facial expressions and gestures helped the participants to recognize who was speaking (A2, B3), but the lack of the opportunity to emphasize

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their own thought processes was perceived as limiting (B123, C3, D3, E13). It was also more difficult to interpret the reaction of the others, as only the avatar of the speaking person showed pre-programmed facial expressions and gestures (A12, B123, C3, D13, E3, F13). One person described, *"The people just sit there and listen to you. And you just do not know whether that is positive or negative* (B1).*"* At the same time, the internet connection sometimes caused delays, so the participants did not always realize that someone else had already started to speak (A2). For these reasons, the participants often interrupted each other at the beginning (A2, B23, C13). To avoid this, five participants actualized a respectful communication affordance and described that as a result everyone listened more closely and waited to let each other speak (A2, B123, C3). In this regard, one participant described the brainstorming session more as a *"constructive discussion* (B2)*"* and considered it unlikely that a *"heated discussion* (B2)*"* would arise. As in her experience, good ideas often result from heated discussions, she perceived this more as a disadvantage.

4.2 Negative Group Effects

Overall, negative group effects occurred only rarely, except for production blocking. According to the participants, this effect was most strongly influenced by VR affordances and constraints, while the other negative group effects were largely influenced by factors such as personality traits or group size. Table 2 gives an overview of how many participants described the occurrence of each negative group effect.

Table 2. Occurrence of Negative Group Effects

Negative Group Effects	*Occurrence*	*Percentage*
Production Blocking	8	44%
Evaluation Apprehension	3	17%
Social Comparison	2	11%
Cognitive Inertia	2	11%
Social Loafing	0	0%

The main reason given by the participants for the occurrence of production blocking was the lack of realistic facial expressions and gestures. As only the avatar of the currently speaking person showed pre-programmed facial expressions and gestures, it was difficult for the remaining participants to signal that they wanted to start speaking (A2, B2, C13). In addition, the seating arrangement in the virtual environment made it difficult for one of the participants to establish eye contact with the other two participants (A1, B2, D3, F23). Due to these reasons, eight participants were speaking less because they *"could not gain the attention of the others* (C1).*"* To counteract this, groups A, B, and C reported that their *"communication has become more polite and friendly over time* (E1).*"* When two participants started to speak simultaneously, they *"stopped and told the other one to talk* (E1).*"* They explicitly emphasized that they had taken care not to interrupt the others; however, this frequently interrupted their

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own train of thought. One participant felt that the brainstorming in VR was *"a bit stiff, because you cannot intervene or catch up ideas. You had to think a little bit about what to say at which time* (B2)*."*

Only three participants described the occurrence of evaluation apprehension. These participants reported that they withheld their contributions because their ideas were not sufficiently elaborated, and one said he "*could not justify it or it would not have contributed to the discussion* (F2)*."* One participant withheld a controversial idea because she was unsure of how the others would react due to the lack of facial expressions (A1). In contrast, another participant stated that the virtual environment counteracted the effect of evaluation apprehension (B2). She explicated that "*in the virtual environment, I definitely had the feeling that I can say whatever I want. I knew it was as strange and new to everyone as it was to me. And then I thought, I will just knock out all my ideas* (B2)*."* The other participants stated that they voiced their opinions freely because of personality characteristics and their willingness to follow the brainstorming rules.

Two participants reported the occurrence of a social comparison, one describing a downward comparison and the other an upward comparison. The participant who made a downward comparison had the impression that she spoke much more than the other two group members. She explained, "*In the beginning I had more speech parts. I did not want to talk so much, then I just backed down* (C1)*."* The person who made the upward comparison noticed that the other group members contributed more to the group's performance than he did, and therefore he wanted to participate more. To explain his fewer speaking parts, the participant said that he was not able to make himself noticeable and did not want to interrupt the others (A2). Therefore, the effect of production blocking can be stated as the reason for this upward comparison. However, most participants said that their focus was on the brainstorming topic, so comparing themselves to the other group members did not even come to their minds.

Only two participants reported the occurrence of cognitive inertia, meaning they deliberately neglected their ideas and followed the opinions of others because it was the more comfortable choice. As an explanation, one person specified that "*within one topic I could express ideas, but when switching to the next theme, I did not want to interrupt the flow* (C1)*."* Eight participants did not have a chance to disagree with the other group members because they had the same opinions. Seven further participants agreed at least partly on opposing views. However, they clarified that they were persuaded by logical arguments and not because it was psychologically more comfortable. Five participants described themselves as keen to debate, and thus they were always introducing new opinions to maintain a lively discussion.

The occurrence of social loafing was not reported. Most of the participants had the impression that all group members put forth equal efforts and that *"it worked very well that someone mentioned something which was then supplemented by the others* (E3)*."* Three participants explained that they were motivated to achieve satisfactory results as a group. The absence of this negative group effect is also explained by the group size. One person explained that a group of three is an appropriate group size, in contrast to a group of four in which *"you can stay out of it very well, if you want* (A3)*."*

5 Discussion

Overall, the participants perceived the conversation in VR as surprisingly natural and described advantages over face-to-face and electronic brainstorming sessions using chats or discussion forums. One advantage is the stronger focus on the brainstorming task by using a head-mounted display combined with an immersive environment However, it has to be mentioned that the participants were distracted from their task by the numerous details within the virtual environment. Bhagwatwar et al. [22] already showed the creativity enhancing effect of virtual environments, but it seems important to keep the distraction potential low. The chosen environment was perceived as safe, pleasant, and relaxing, allowing the participants to express their ideas freely. These aspects had a positive influence on idea generation, and at the same time negative group effects occurred rarely. Furthermore, only production blocking and evaluation apprehension could be associated with the affordances and constraints of the used VR application and hardware. Figure 2 visualizes the affordance and constraint network [34] that allows us to explain the occurrence of these two negative group effects.

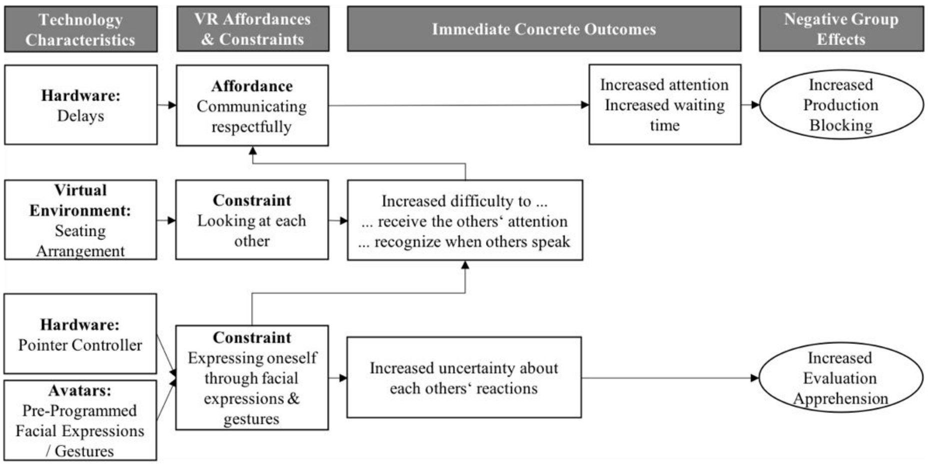

Figure 2. Affordance and Constraint Network

The affordance and constraint network illustrates that the limitations of the used VR application and hardware afforded and constrained communicative actions (1. Communicating respectfully, 2. Looking at each other, and 3. Expressing oneself through facial expressions and gestures). The actualization of the afforded communicative action and the tried actualization of the two constrained communicative actions resulted in immediate concrete outcomes of which some directly manifested in negative group effects. For example, through the actualization of the respectful communication affordance the participants paid more attention to the others and waited longer until it was their turn to express an idea. These outcomes describe the production blocking effect as the participants were interrupted in their

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own train of thought while listening more closely to the other participants and waiting for their turn. The affordance and constraint network also shows that sometimes the outcomes resulting from the tried actualization of a constrained communicative action can result in the emergence of a new affordance [33]. In our study, the seating arrangement constrained the possibility to look at each other which resulted in an increased difficulty to recognize when others started to speak and receive the others attention. As a result, the participants actualized the respectful communication affordance.

Originally, Burton-Jones and Volkoff [34] proposed the affordance network approach to explain effective use of an IT system through the successful actualization of affordances. Therefore, the original affordance network approach only focuses on the actualization of affordances but does not consider the role of constraints. The most obvious solution would be to extend the affordance network approach by simply incorporating constraint-outcome units in addition to affordance-outcome units. However, outcomes result from the actualization of affordances and it is not clear yet what the counterpart of actualization is when it comes to constraints. According to Strong et al. [32], affordance actualization means performing various actions to realize action potentials (affordances). However, constraints are limited action potentials – this raises the question if it is possible to actualize constraints or in other words perform actions to realize a limited action potential. Let us look at an example from our study: The VR application constrained the possibility to express oneself through facial expressions and gestures. Therefore, the participants were not able to perform any actions to realize this limited action potential. However, they tried to do that by changing their facial expressions in the real world and hoping that their expressions would be transferred into the virtual environment. Only because the participants actually tried to realize the limited action potential, they noticed negative outcomes such as an increased uncertainty about the others' reactions which manifested in the effect of evaluation apprehension. To apply the affordance network approach to the study of negative groups effects, we therefore suggest distinguishing between actualization of affordances and tried actualization of constraints. This allows us to extend the affordance network approach by incorporating both affordance-outcome units and constraint-outcome units.

6 Conclusion

This study aimed to understand how VR affordances and constraints affect the occurrence of negative group effects during VR brainstorming sessions. Therefore, we conducted a qualitative study with 18 participants consisting of VR brainstorming sessions and interviews. The results indicate that VR might be promising to support geographically dispersed teams in idea generation processes. We found that production blocking and evaluation apprehension were the only negative group effects associated with the affordances and constraints of the provided VR application and hardware. To explain the occurrence of negative group effects, we applied the affordance network approach of Burton-Jones and Volkoff [34]. In this context, we

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suggest extending the approach by incorporating constraint-outcome units in addition to affordance-outcome units. We further contribute a discussion about whether the notion of affordance actualization can be transferred to constraints.

There is already a lot of research on negative group effects in EBS such as chats or discussion forums. Our research expands this research stream by providing first insights into negative group effects in VR, but of course our results are not generalizable for all VR applications and headsets. In our study, we used the application vTime XR in combination with the portable headset Oculus Go. The selection of the software and hardware constitutes a limitation of our study as vTime XR did not provide visualization tools such as a shared whiteboard. Furthermore, the Oculus Go did not support 6DOF tracking and the pointer controller limited the participants' possibilities to express themselves through gestures and facial expressions. Future research will therefore have to investigate to what extent the identified affordance and constraints can be transferred to other VR technologies that can support idea generation processes (e.g. the 6DOF headset Oculus Quest). In the future, it might also be interesting to investigate how different avatar designs affect negative group effects in hierarchical structures. Furthermore, research is needed on how virtual brainstorming environments should be designed to afford creative thinking without being distracting.

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Paradoxical Tensions Between Social Media Affordances and Constraints for Collective Action – Analysing the Interplay of Organisations Pursuing Different Environmental Policy Goals

Stefan Stieglitz[a], Jennifer Fromm[b], and Milad Mirbabaie[c]

[a] *University of Potsdam, Germany; stefan.stieglitz@uni-potsdam.de*

[b] *University of Duisburg-Essen, Germany; jennifer.fromm@uni-due.de*

[c] *Paderborn University, Germany; milad.mirbabaie@uni-paderborn.de*

Abstract

In recent years, social media have emerged as a central platform for political engagement and collective action. Several studies have already identified social media affordances and constraints for collective action. However, it is still unclear how actors pursuing different environmental policy goals on the same platform mutually influence each other regarding affordance actualisation and the perception of constraints. In this study, we conducted interviews with social media managers of social movements for climate justice and organisations pursuing different environmental policy goals in Germany. We analyse three paradoxical tensions between social media affordances and constraints for collective action arising from the interaction of actors pursuing different environmental policy goals. Thereby, we contribute a nuanced view on the effective use of social media for collective action. Our study also has implications for practice because members of other social movements can use the results to develop an effective social media strategy.

Keywords: social movement; collective action; technology affordances and constraints theory; social media; qualitative research

Introduction

There is already extensive research on the action possibilities social media offer for collective action, or so-called affordances (Comunello et al., 2016; Harindranath et al., 2015; Khazraee & Novak, 2018; McKenna, 2019; Sæbø et al., 2020; Tim et al., 2017; Zheng & Yu, 2016). Affordances are defined as 'the possibilities for goal-oriented action afforded to specified user groups by technical objects' (Markus & Silver, 2008, p. 622). To reach movement goals and, thus, use social media effectively, action potentials must be successfully actualised (Burton-Jones & Volkoff, 2017). However, previous studies on affordance actualisation have typically considered one or more actors who share the same overarching goal in using the same technology. For example, Strong et al. (2014), who first theorised regarding the affordance actualisation process, distinguished between different organisational roles among users of an electronic medical record system, but the users shared the overall goal of improving healthcare. However, when social movements such as Fridays for Future use social media, they are using the same platform as organisations with different goals, such as the counter-movement Fridays for Hubraum, in which car enthusiasts speak out against environmental zones, driving bans, and CO2 taxes (Herrmann et al., 2022).

Thus, information systems researchers highlighted the importance to investigate the influence of external stakeholders on organisational affordance actualisation processes (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Sæbø et al., 2020). Furthermore, the actualisation of affordances can have paradoxical effects in the sense that they can simultaneously promote and hinder the achievement of goals (Ciriello et al., 2019; Majchrzak et al., 2013; Tim et al., 2017). These paradoxical tensions between affordances and constraints might be further intensified when organisations pursuing different goals actualise affordances on the same platform. Thus, we posit that the affordance actualisation process of social movements cannot be fully understood in isolation but, rather, must be viewed in light of the potential influence of the social media activities of organisations pursuing different goals.

In our view, the concept of constraints, understood as the counterpart of affordances, may be a promising one to adopt in studying the interplay between affordance actualisation processes by multiple organisations with different goals. The idea is that the social media activities of organisations with different goals could lead to the emergence of constraints for a social movement, and vice versa. Thus far, only few studies have investigated the social media constraints perceived by social movements (Comunello et al., 2016; Dumitrica & Felt, 2019). In these studies, constraints are understood as barriers to goal achievement; however, the connection between the perception of constraints and actualisation of affordances has been neglected thus far. Hence, we ask the following research question: *What tensions arise between social media affordances and constraints through the interaction of social movements for climate justice and actors pursuing different environmental policy goals?*

By answering this research question through a technology-affordances-and-constraints lens, we contribute to information systems research as follows: We distinguish between self-imposed constraints and constraints that emerge through the affordance actualisations of other actors pursuing different environmental policy goals. Furthermore, we highlight paradoxical tensions between affordances and constraints arising from the affordance actualisations of organisations pursuing different environmental policy goals. We also examine which strategies actors employ to resolve these paradoxical tensions. This advances the understanding of technology affordances and constraints in information systems research, which have, thus far, mostly been examined in isolation and without considering the influence of actors pursuing different goals on the same platform. To answer the research question, we conducted 30 interviews with social media managers of social movements for climate justice and six interviews with members of organisations that pursue different environmental policy goals.

Theoretical Background

Technology Affordances and Constraints Theory

In the field of ecological psychology, where the concept of affordances has its roots, it originally referred to both the possibilities for action and the limits or dangers that determine how animals can interact with their environment (Gibson, 1979). The concept was adapted in other fields such as human-computer interaction where affordances have been seen as a way for designers to provide cues about how a technological artefact functions or how an object can be used (Norman, 1988). In the field of information systems, technology affordances and constraints theory was proposed to study the interaction of users and information systems, such as social media (Majchrzak & Markus, 2012). Here, affordances are defined as 'the potential for behaviours associated with achieving an immediate concrete outcome and arising from the relation between an artifact and a goal-oriented actor or actors' (Strong et al., p. 69).

Both the user and the system play a role in the perception of affordances and constraints. Users require the ability to grasp affordances, but a system can also facilitate the perception of affordances by effectively communicating meaning and values (Grgecic, Holten, & Rosenkranz, 2015). The affordances and constraints of one and the same technology can be perceived differently depending on the user's goals and mental models (Mettler & Wulf, 2019; Chan, Cheung, & Wong, 2019). Users construct perceptions of whether a technology affords or constrains their ability to achieve their goals (Leonardi, 2011; Jung & Lyytinnen, 2014; Boukef & Charki, 2019). External factors, such as the historical and socio-cultural context, the organisational context, as well as user experience, knowledge and skills, can enable or inhibit the perception of specific affordances (Jung & Lyytinen, 2014; Karlsen et al., 2019; Lehrer et al., 2018).

Affordance actualisation comprises ‘the actions taken by actors as they take advantage of one or more affordances through their use of the technology to achieve immediate concrete outcomes in support of organisational goals’ (Strong et al., 2014, p. 70). The actions users take to actualise the same affordance may differ depending on their goals (Strong et al., 2014). In organisational contexts, it is assumed that the affordance actualisations of individuals result in immediate, concrete outcomes, which collectively contribute to the achievement of organisational goals (Strong et al., 2014). However, affordance actualisation can also have paradoxical effects (Majchrzak et al., 2013; Tim et al., 2017). For example, the actualisation of social media affordances can have both helping and hindering effects on productive knowledge conversations (Majchrzak et al., 2013). To resolve paradoxical tensions, users can either apply avoidance or confrontation strategies, that is, they can reduce affordance actualisation or try to better understand and use the affordances and constraints of a technology (Jarvenpaa & Lang, 2005). External factors such as organisational culture, standards and policies can enable or inhibit the actualisation of affordances (Strong et al., 2014). The actualisation of affordances can build knowledge and skills, enabling the user to perceive additional affordances over time or recognise new goals that could be achieved using the technology (Grgecic, Holten, & Rosenkranz, 2015; Leonardi, 2011; Strong et al., 2014).

Constraints can inhibit actors from achieving their goals and thus prevent the actualisation of desired action potentials and the achievement of associated outcomes

(Bernhard et al., 2013; Bobsin et al., 2019; Ens et al., 2018; Majchrzak & Markus, 2012). The perception of constraints can lead to affordances not being realised or to actualisation not resulting in the desired outcome (Bobsin et al., 2019; Goh et al., 2011; Leonardi, 2011). The relationship between affordances and constraints also includes key elements of paradoxes, namely contradiction and interdependence (Smith & Lewis, 2011). Related to this, Ciriello et al. (2019) highlighted the paradoxical tensions between technology affordances and constraints because, for example, the malleability of presentation software enables users to express creative ideas while the provided templates can constrain creative interaction. To date, only a few studies have considered both affordances and constraints with the same level of focus (Amankwah-Sarfo et al., 2019; Ciriello et al., 2019; Leonardi, 2011; Mettler & Wulf, 2019). Many studies have focused on affordances, while other studies only consider general obstacles or disadvantages associated with technologies, without discussing the relationship to affordance actualisation (Fromm et al., 2020). We aim to analyse the paradoxical tensions between social media affordances and constraints while considering the mutual influence of actors pursuing different environmental policy goals on the same platform.

How Social Movements Use Social Media

The term 'social movements' refers to 'networks of informal interactions between a plurality of individuals, groups and/or organizations, engaged in political or cultural conflicts, on the basis of shared collective identities' (Diani, 1992, p. 1). New social movements are those that emerged after the industrial era, such as the environmental, feminist, and peace movements (Boggs, 1986). In the context of social movements, collective action can be described by formally organised communities that are characterised by a concrete goal, a high degree of organisation, and a strong group identity (Bennett & Segerberg, 2011; Olsen, 1971).

In recent years, street activism has increasingly been supplemented by digital activism, for example, via social media (Millward & Takhar, 2019). Social media are defined as ‘a group of Internet-based applications which are built on the ideological and technological foundations of Web 2.0 and enable the creation and exchange of user-generated content’ (Kaplan & Haenlein, 2010, p. 61). These platforms enable the formation of a collective identity, and collective action takes on a personal character through social networks (Bennet & Segerberg, 2011; Khazraee & Novak, 2018). Furthermore, social media enables the building of social capital, which leads to increased participation in social movements (Hwang & Kim, 2015). Social media can support traditional offline activism by facilitating rapid information diffusion and mobilisation efforts globally (Harlow, 2012; Hwang & Kim, 2015; Van Laer & Van Aelst, 2010). Digital activism includes, for example, liking and sharing posts, signing digital petitions, and supporting e-funding campaigns (George & Leidner, 2019). The emergence of digital activism, in addition to traditional offline activism, can be supportive but also difficult for social movements because activities on the part of social media users can challenge the values of the movement (Selander & Jarvenpaa, 2016). Furthermore, the low level of effort and resources required to engage in digital activism can give rise to counter-movements (George & Leidner, 2019).

Social Media Affordances and Constraints for Collective Action

Social media offer several affordances for collective action, such as mobilising resources and volunteers, distributed collaboration, agenda setting, and coordinating massive, staged acts (Comunello et al., 2016; Harindranath et al., 2015; Khazraee & Novak, 2018; McKenna, 2019; Sæbø et al., 2020; Tim et al., 2017; Vaast et al., 2017; Zheng & Yu, 2016). A study of social movements in Egypt covers a wide range of social media affordances for collective action: 1) information validation, 2) information supplementation, 3) perpetual self-updating, 4) perpetual mass-updating, 5) self-reportage, 6) monitoring and influencing, 7) self-organisation, 8) interactive communication, and 9) self-presentation (Harindranath et al., 2015). Table 1 provides an overview of social media affordances for collective action found in previous studies. Social movements adapt their social media use based on platform-specific perceptions of affordances and constraints (Comunello et al., 2016). For example, Twitter is used for rapid information gathering and dissemination, while Facebook is used for interaction and organisation, and YouTube is seen as an alternative to traditional television (Benroider et al., 2016; Comunello et al., 2016; Harindranath et al., 2015).

[Table 1 near here]

In the context of collective action, previous research has identified emerging roles that are mutually interdependent in their actualisation of affordances (Vaast et al., 2017). For example, advocates are needed to initiate and guide collective action on social media through original posts, while amplifiers are required to draw long-lasting attention to these posts through sharing activities (Vaast et al., 2017). Furthermore, the combined actualisation of multiple social media affordances is required to create the antecedents of collective action (Sæbø et al., 2020). However, because social media platforms are not specifically designed for collective action, social movements may also need to use affordances creatively to achieve their goals (McKenna, 2019). Moreover, the actualisation of social media affordances cannot only result in positive outcomes; it can also have negative consequences for social movements (Tim et al., 2017). For example, social media may enable information democratisation, but paradoxically, the actualisation may also result in information cluttering (Tim et al., 2017).

As compared to affordance research, only a few studies have analysed social media constraints for collective action, referring to them as barriers, constraining factors, or unintended consequences (Comunello et al., 2016; Dumitrica & Felt, 2019; Tim et al., 2017). Table 2 provides a summary of social media constraints for collective action identified in previous research. Based on three Canadian case studies, Dumitrica and Felt (2019) identified three categories of social media barriers to collective action. Technical barriers included restrictions on the dissemination of posts due to predefined network logics and algorithms (Dumitrica & Felt, 2019), filter bubbles (Tim et al., 2017; Dumitrica & Felt, 2019), information overload (Comunello et al., 2016; Tim et al., 2017), the restricted length of postings, and privacy concerns (Comunello et al., 2016). Interactional barriers summarised the dissemination of misinformation by users who do not agree with the intentions of the movement (Dumitrica & Felt, 2019; Tim et al., 2017). Regarding personal barriers, previous studies cited a lack knowledge and skills (Comunello et al., 2016), emotional strain, and career risks associated with social media use for the movement (Dumitrica & Felt, 2019). Our study advances knowledge on social media constraints for collective action with a focus on how the affordance actualisations of actors pursuing different environmental policy goals influences the perception of constraints.

[Table 2 near here]

Research Design

Research Context – Social Movements for Climate Justice

The Fridays for Future climate movement and their subgroups, such as Health for Future, Vegans for Future, Students for Future, and Scientists for Future served as the research context for our study. These highly organised movements make intensive use of a wide range of social media channels and, thereby, successfully mobilise people for collective action. Thus, climate activists could provide detailed insights into affordance actualisation and constraint perception regarding collective action on social media. With over three million demonstrators worldwide, Fridays for Future is one of the most significant social movements of this time (Fridays for Future, 2020a). The movement advocates for rapid political and social change to address the climate crisis and limit global warming to a maximum of 1.5 degrees. Fridays for Future is a coordinated movement that describes itself as a ‘non-partisan movement of like-minded climate activists’ (Fridays for Future, 2020b). In Germany, the organisation and coordination of demonstrations and media appearances take place through more than 500 local groups and thematic working groups with respective delegates.

Starting with Greta Thunberg, who demonstrated in front of the Swedish Parliament during her school days, the movement was primarily driven by students who went on strike during school hours on Fridays (Wahlström et al., 2019). Meanwhile, several subgroups were initiated, all with the same goal: averting the climate crisis. While activists have been striking since 2018 and gained momentum via social media, the focus has increasingly shifted to social media over the course of the COVID-19 pandemic in 2020. Through online actions, such as the largest online network strike, activists use their media outreach to draw attention to existing threats and expand the network of activists. Their call to share posts with the #NetStrikeForClimate hashtag in April 2020 was answered by over 280,000 people in 150 countries (Fridays for Future, 2020a).

Recruitment of Interviewees

To address the research gap, we followed a qualitative research approach, which is well suited to answering ‘how’ and ‘why’ research questions, building theory in new research areas, and providing rich insights into the subjective views of respondents (Flick, Kardorff, & Steinke, 2004). We conducted semi-structured interviews with 30

German activists who managed the social media channels of social movements for climate justice, i.e., Fridays for Future, Health for Future, Vegans for Future, Students for Future, and Scientists for Future. The interviews focused on social media managers and not personal users because we were interested in affordance actualisation and the influence of constraints at an organisational level. We assumed that the official social media managers would be more familiar with the organisational goals and social media strategy than personal users.

To reach our target group, we recruited participants directly through social media. We began with a hashtag search to find suitable participants. These included, for example, #klimastreik (engl. climate strike), #fridaysforfuturegermany, and #klimagerechtigkeit (engl. climate justice). We contacted account holders who posted on these topics after screening their profiles for content related to the climate movement. Through friend and follower lists, we were able to identify further potential participants. On Facebook, we also shared the call for study participation in groups related to social movements for climate justice. In addition, volunteers contacted us after the movement's press team and other activists forwarded the request. Table 3 provides an overview of the participants.

[Table 3 near here]

The interviews revealed that constraints on the climate movement often arise from affordance actualisations by organisations pursuing different environmental policy goals. As examples, climate activists mentioned the right-wing populist party Alternative for Germany, a counter-movement called Fridays for Hubraum that was founded by car enthusiasts, and a group of industrial farmers calling themselves Farmers for Future. We attempted to recruit social media managers of organisations pursuing different environmental policy goals to triangulate our findings. To do so, we looked up the social media accounts of organisations with different environmental policy goals that were mentioned in the interviews with the social media managers of social movements for climate justice. Inclusion criteria were as follows: (1) The organisation regularly posts environmental policy content on at least one social media platform and (2) interactions with social movements for climate justice are evident (e.g., posts about social movements or individual members, comments by members of social movements). Exclusion criteria were: (1) The organisation posts very rarely about environmental issues, (2) hardly interacts with social movements for climate justice, or (3) the last time was more than a year ago. Based on this initial selection of accounts, we identified further relevant accounts by checking accounts in follower lists or similar accounts suggested by the respective platform.

This proved to be a difficult task, as members of these organisations must often deal with negative press reports and, accordingly, display a certain amount of caution, sometimes even refusal, when asked for interviews. Our strategy was to gain their trust via as much transparency as possible and, for example, sending them the interview guide in advance if requested. Nevertheless, the response rate was low, and some contact persons did not agree with the interview guide despite several adjustments. Similar problems in recruiting participants also appear in research on anti-brand communities, in which it is also of importance to build trust with the communities (Dessart, Veloutsou, & Morgan-Thomas, 2020). Further complicating the matter, Meta has imposed restrictions on one of our Facebook accounts due to ‘connections with non-trusted accounts’. A request for reconsideration resulted in a permanent restriction.

However, we were able to recruit a member of the German federal parliament, a member of the state parliament, and two local politicians from the right-wing populist party Alternative for Germany. This party admits that climate change exists but denies that it is caused by humans. The party suggests that a radical energy transition may lead to supply shortages and an explosion in electricity prices. Accordingly, it advocates the continued operation of coal-fired and nuclear power plants until baseload supplies can be provided by alternative energies.

Furthermore, one of the founders of the German Combustion Engine Association agreed to an interview. This association opposes the abolition of the internal combustion engine in favour of electric motors because the production of batteries is resource intensive and harmful to the environment. Instead, the association advocates that vehicles be manufactured in such a way that they can be repaired easily, and repairs can also become less expensive.

We were also able to conduct an interview with the social media manager of the Schleswig-Holstein Farmers' Association. This association represents the interests of the agricultural sector. In principle, the association is in favour of making agriculture more sustainable, but it holds that the economic viability of family farms should be maintained. Currently, they see that farmers are required to implement more and more ecological protection measures, which means that family farms are no longer economically viable. Accordingly, the association is committed to both, a sustainable and economical agriculture.

It should be mentioned that all these organisations have described the goals of social movements for climate justice as good and important. However, the climate movement advocates the immediate implementation of radical environmental measures, while the other organisations advocate for slower change to maintain a stable economy. Accordingly, the Alternative for Germany, German Combustion Engine Association, and Schleswig-Holstein Farmers' Association can be described as organisations with different environmental policy goals as compared to social movements for climate justice. Table 4 provides an overview of the participants from these organisations. It is noticeable that the interviewees differ from the interviewees of the social movements for climate justice regarding the composition of gender and age. However, this reflects actual differences in the composition of the organisations interviewed.

[Table 4 near here]

Interview Guide

We developed an interview guide that left room for follow-up questions. Before the interview, the respondents were informed about the topic, interview procedure, data handling, and their rights as participants. The following topics were addressed in the interviews: (1) Socio-demographics and role in the respective organisation, (2) Goals of social media use and platforms used, (3) Actualised affordances, (4) Perceived constraints, (5) Reasons for using multiple social media platforms, and (6) Impact of constraint perception on affordance actualisation. At the end of the interviews, we thanked the respondents for their participation and asked if they wanted to add anything else on the topic. Example questions for each topic can be found in Table 5.

[Table 5 near here]

The selection of interview topics was guided by our research question and theoretical background. Our research question focuses on tensions between social media affordances and constraints, which we considered difficult for interviewees to answer without a step-by-step approach. Therefore, the first parts of the interview addressed important building blocks, such as the goals of social media use, because affordances are goal-oriented action potentials. In the further course, actualised affordances and perceived constraints were first discussed individually so that both topics could be discussed in conjunction at the end of the interview.

First, we asked the participants which social media platforms they use. To identify affordances, we then presented them with a list of features of these platforms (see column 2 from the table in Appendix B) and asked them which action potentials these features offer that can help them achieve their organisational goals. This procedure was helpful because, in this way, the participants distinguished more clearly between technology features and affordances by using phrases such as ‘This feature allows me to do [affordance]’. Also, we avoided the rather abstract term ‘affordance’ and saw it as our task as researchers to assign the statements of the participants to affordance categories in the later analysis.

Originally, the interviews should focus on social media platforms. However, the interviewees frequently emphasised the importance of instant messengers, which also provide the opportunity for self-presentation via status updates, visibly connecting with people in group chats, and sharing user-generated content, although content is only visible for a specific user or user group. Therefore, we decided to broaden our scope to include instant messengers such as WhatsApp and Telegram. A list of the features provided by social media platforms and instant messengers in Germany at the time of data collection can be found in Appendix B.

The interviews were recorded and transcribed verbatim. On average, the interviews lasted 70 minutes, and they ranged from 43 to 95 minutes. The interviews were conducted and transcribed in German; relevant quotes cited in this article were translated by the authors.

Qualitative Content Analysis

Following a positivist qualitative approach, we engaged in an extensive reading of the literature before data collection and analysis, which allowed us to improve the selection of participants and the development of interview questions (Berkovich, 2017). Another advantage of the approach is the use of systematic research protocols and techniques to summarise identified patterns as generalised findings through non-statistical methods (Cassell, Cunliffe, & Grandy, 2017). To analyse the interviews, we conducted a qualitative content analysis applying the active categorisation framework for theory development (Grodal, Anteby, & Holm, 2021). The framework describes eight analytical moves that researchers can apply to move from data to theory. The idea behind the framework is that qualitative researchers can achieve rigor in their analysis by being more reflexive and transparent about their analysis process. In Table 6, we explicate how we applied each analytical move in our study.

[Table 6 near here]

At the beginning of the analysis process, two coders agreed on questions to ask themselves while reading the material. Then, they coded text passages they perceived as relevant to these questions independently from each other. Afterward, they discussed which elements of the interview material they found most surprising and which categories could be dropped, merged, or split. We created an initial coding guide including definitions and anchor examples for different categories of actualised affordances and perceived constraints. The first coder used the coding guide to adjust the initial coding. Afterward, both coders compared categories of actualised affordances and perceived constraints to theorise about the relationship between them. The analysis resulted in three paradoxical tensions between social media affordances and constraints arising from the affordance actualisations of actors pursuing different environmental policy goals. The agreed upon definitions for the final categories were updated in the coding guide (see Appendix A). To check for intercoder reliability, the second coder coded 20% of the text material again with the final coding guide, and we calculated a Cohen's kappa coefficient of .82 (Cohen, 1960), which can be interpreted as very good

(Landis & Koch, 1977).

Results

Tension Between the Affordance of Informational Education and the Constraint of False Information, Ideology, and Propaganda

With 25 climate activists, the majority uses social media to actualise an informational education affordance. According to a spokesman of the national Fridays for Future social media working group, 'one of the biggest goals is education, information about the climate crisis. There has been far too little information work in this direction in recent years. For that, social media is a huge platform we can use, apart from demos' (Fridays for Future, national level, FFF08). To educate people, climate activists see the greatest potential on Instagram 'where we bring all the beautiful infographics and share pics' (Fridays for Future, local level, FFF02). In doing so, climate activists attach great importance to the image descriptions making sure that 'those who really want to read it also get good scientific sources and good correct information' (Vegans for Future, local level, VFF01). Furthermore, they strategically use hashtags 'as a method to get the information into other filter bubbles' (Fridays for Future, local level, FFF09).

Another part of actualising the informational education affordance includes providing information about demos such as 'how many people are on the demo, when does it start, what is the demo route? Who is speaking next? That's information that's being pushed on Twitter' (Fridays for Future, local level, FFF03).

Especially climate activists on the national level also emphasise the importance of 'pointing out false information statements of politicians' (Fridays for Future, local and national level, FFF01) and 'reacting quickly if any fake news is spread in local newspapers' (Fridays for Future, local and national level, FFF04).

Especially from the interaction with the Alternative for Germany arises a tension. While climate activists, according to their own statements, place a lot of emphasis on disseminating correct information supported by scientific sources, this is doubted by members of the Alternative for Germany. As one member puts it: ‘It is a noble cause to save the climate, but then they must also back up with facts that mankind is responsible for the entire global warming. So far, no one has succeeded in doing that’ (Alternative for Germany, local level, AFG03). A member of the Bavarian state parliament is convinced that ‘this whole environmental movement has a lot of ideology in it. Partly antisemitic, cultural-marxist, anti-capitalist, these are things that you actually know from communist movements. The climate movement is very strongly infiltrated. There is hardly anyone who checks their content for accuracy. There are so-called fact checkers, but these fact checkers are also just an ideology department from the left bubble. Environmental protection is natural science, but this whole Fridays for Future issue is a pure ideology event’ (Alternative for Germany, state level, AFG01). He also gives an example to illustrate that in his view the climate movement does not disseminate information but political propaganda: ‘Some people say we have to save the world by converting individual transport to electric mobility. Yes, that's environmental protection, it's green. Not true at all. Pure propaganda’ (Alternative for Germany, state level, AFG01).

The German Combustion Engine Association and the Schleswig-Holstein Farmers’ Association do not directly criticise the information activities of social movements for climate justice. However, the Board of the German Combustion Engine Association raises the issue that even official sources such as the Federal Ministry of the Environment spread only half truths ‘because you will only find the figures indicating the amount of green electricity produced. But that says nothing about the amount of green electricity that has been used in Germany. These are exactly the figures that we disseminate. To say, look, there are always two sides to a coin, and if you only show one and don't tell people about the other, that's also a kind of information that influences people' (GCEA). The results highlight the tension that both social movements for climate justice and actors pursuing different environmental policy goals perceive the social media constraint of false information although all actors claim that they use social media to disseminate correct information.

Tension Between the Affordance of Emotional Storytelling and the Constraint of Shadow Bans and Content Deletion

Two thirds of the climate activists actualise an emotional storytelling affordance on social media. They strategically use image and video content because 'visual language also conveys emotions. That sounds very tactical, of course, but that also plays a role' (Fridays for Future, local level, FFF05). As a spokeswoman of the national Fridays for Future social media working group explains: 'Videos and photos are generally content that arouse emotions. So, it's a lot of calculation that you create a reference to certain topics and try to post beautiful pictures. To somehow make the whole thing a bit more appealing to people' (Fridays for Future, local and national level, FFF01). She further emphasises the importance of 'speaking into the camera yourself or filming things which is about giving the movement a face' (Fridays for Future, local and national level, FFF01). Climate activists also use livestreams to convey positive emotions during demos because 'people who are not at the demo see that there are many of us and that it might have been worthwhile to come there if the atmosphere is good' (Vegans for Future, local level, VFF01). Another aspect of the emotional storytelling affordance is to create a sense of cohesion within the movement. This is achieved by posting memes and insider jokes which 'is not about reaching people, but rather motivating the people who are already active. This form of humour is a kind of care package for one’s own group and to strengthen cohesion’ (Fridays for Future, local level, FFF03). Furthermore, a corporate identity plays an important role where they ‘use the same colour patterns and so on across several accounts, also creating this group feeling’ (Fridays for Future, local level, FFF10). In summary, social movements for climate justice actualise an emotional storytelling affordance with a focus on evoking positive emotions to mobilise people and strengthen cohesion within the movement.

Actors pursuing different environmental policy goals also actualise an emotional storytelling affordance, but rather in a provocative way to catch the attention of social media users. As the social media manager of the Schleswig-Holstein Farmers’ Association explains, ‘it's not enough to post information on Facebook. You first have to gain reach and attention. That means we also provoke with headlines, but in terms of content we try to make it very fact-oriented’ (SHFA). The Board of the German Combustion Engine Association also observes that ‘the posts that do best are the ones that stand out visually with some tabloid newspaper headlines. If I post a picture that is already an uproar and a headline that really gets everyone going, then this post gets significantly more attention than one that deals with the problem in more depth. And you have to do that, because we want to get our message across’ (GCEA). It has to be mentioned that both organisations perceive sensational headlines as necessary to catch the attention of social media users, hoping that they will then also engage more deeply with informative and fact-based content on their channels. For example, the Board of the German Combustion Engine Association says: ‘Of course we won't spread any lies, but there are things about this topic that have an emotional impact. And of course, we use them, otherwise we would never have reached such high numbers of followers. That gets attention and then maybe people come to the site and can actually learn something’

(GCEA). The Alternative for Germany takes this strategy to the extreme and publishes provocative posts that are close to being deleted by the platform provider ‘to wake people up a bit, to get them interested. Because if I write without emotion, then people don't look at it. But if you put something in that's pretty close to being blocked, then they look’ (Alternative for Germany, local level, AFG03). The German Combustion Engine Association and Alternative for Germany also follow discussions outside their community to lurk on sore spots of the climate movement and use these against them. The Board of the German Combustion Engine Association perceives this to be ‘one of the most interesting parts on social media, that I can go into spaces that don't correspond to my community. And in these spaces, I can observe how they talk about their problems. And then I can pull the lever and say, look, even the one hundred percent advocates of e-mobility admit what significant problems they have’ (GCEA). The Alternative for Germany, on the other hand, uses the public’s anger about climate strikes to grab the attention of social media users: ‘So, it's getting more and more extreme [the actions of climate activists] and the public's aversion to it is also getting bigger and bigger. And I take advantage of that. I'm even part of the mailing list so that I can find out early what campaigns they're doing’ (Alternative for Germany, local level, AFG04). A spokeswoman of the national Fridays for Future social media working groups admits that they also apply this strategy to a certain extent but perceives that they as a movement are more often on the receiving end: ‘Following other profiles is quite often a case of lurking on the sore spot. So, when does a statement come that you can say something against? Maybe we don't do that to such an extreme, but other people do that to ourselves’ (Fridays for Future, local and national level, FFF01). Taken together, actors with different environmental policy goals actualise the emotional storytelling affordance by taking advantage of the public's anger and vulnerabilities of the climate movement to capture the attention of social media users.

As a result, the Alternative for Germany in particular has to deal with the constraint of shadow bans and content deletion 'because the social networks are tightening their rules more and more. And our opponents are taking advantage of that. Anything that even comes close to not being verified is reported. And the problem is not so much the blocking, but the loss of reach' (Alternative for Germany, local level, AFG04). However, the German Combustion Engine Association and Fridays for Future also have to deal with bans and content deletions because actors pursuing different environmental policy goals report their posts in a coordinated manner. According to a spokeswoman of the national Fridays for Future social media working group, the problem is 'that it's very easy for counter-groups to form, it's very easy for people to report you, and then tweets are blocked because a tweet is temporarily blocked after a certain number of reports. That can lead to very severe restrictions' (Fridays for Future, local and national level, FFF01). Likewise, the Board of the German Combustion Engine explains: 'There are also many people on our site who have a different opinion. And if you hit some point that they don't like, then of course they start reacting on Facebook and report us for fake news or try to say that we've violated some community standards' (GCEA).

Members of the Alternative for Germany feel that their fundamental rights are restricted by 'these agencies that work for Facebook, Twitter, YouTube. These are left-wing activists, in fact. And they block an awful lot. They kick you out, they delete channels, they delete videos. This permanent censorship, it's psychological terror. When you can't present your political content' (Alternative for Germany, state level, AFG01). According to a member of the Alternative for Germany with a legal background, 'that violates freedom of speech considerably’ (Alternative for Germany, national level, AFG02). In addition, members of the Alternative for Germany perceive an unfair assessment of reported posts on the behalf of platform operators. While they receive frequent bans, they themselves ‘have not yet obtained a blocking of any other pages, no matter how disgusting that was, what the people have posted against us. You can see a very strong imbalance in the platforms, how they pursue this. You can clearly see that some people are set, they are allowed to do that, and other people are not allowed to do that’ (Alternative for Germany, local level, AFG04). Confirming this impression, the Board of the German Combustion Engine Association ‘noticed that Facebook was quite lenient with us. Because I couldn't deny the impression that they might be interested in having a lot of traffic and would rather turn a blind eye. And on the other hand, I think, if there is less traffic, then they are also willing to step on your toes more’ (GCEA).

To avoid the constraint of shadow bans and content deletion, three members of the Alternative for Germany started information channels on Telegram ‘because the only platform that has never caused any problems so far is Telegram’ (Alternative for Germany, state level, AFG01). Another way to bypass this constraint is ‘writing the posts in a way where you realise, yes, it’s borderline. It could be that one misunderstands it somewhat, but it’s just tolerated. And that’s a very fine line so that you get your message across but where the secret police don’t delete anything’ (Alternative for Germany, local level, AFG03).

Tension Between the Affordance of Interactive Networking and the Constraint of Hate Speech and Coordinated Shitstorms

All interviewed climate activists actualise the social media affordance of interactive networking. One aspect of this affordance actualisation includes supporting other climate activists by liking and commenting their posts: ‘What I do is that I go to the accounts of Fridays for Future activists, for example, and that I then comment “Great page” to support them’ (Health for Future, local level, HFF01). As a result, ‘it certainly strengthens the relationship with each other when you tag each other in stories and interact with each other’ (Fridays for Future, local and national level, FFF01). However, for many climate activists ‘liking is something strategic. I know from my experience in the field that you have to like a lot to get something back and that you also have to like posts that you might not find that great. But you know that generates followers and that gives us reach’ (Health for Future, local level, HFF02). According to Fridays for Future, it is of great importance to have ‘interaction with other sites, with alliance partners. For example, Nature and Biodiversity Conservation Union Germany, Greenpeace and so on. For large demonstrations, we always form alliances, and it is of course important that the pages of the others are liked and that there is interaction’ (Fridays for Future, local level, FFF12). To support other organisations fighting for climate justice, they use their Instagram stories to ‘call for demos that we have not organised ourselves, but which we still find worth supporting. We don't have to write much about it, but we support other groups with it. And we also ask other groups, for example, about the net strike or the public climate school, whether they also want to share our content’ (Students for Future, local level, StFF01).

The formation of support networks enables them to set trends on Twitter and influence public discourse, ‘meaning that if we want a topic to become important on Twitter, we can do it. The latest example is #futureofGAP. It's about the new regulation of agricultural policy at the EU level. Because we have called on our community to tweet under the hashtag, it is now already number two in the Twitter trends. We are explicitly planning something like this because it has been proven that Twitter trends are more likely to be picked up by the media' (Fridays for Future, national level, FFF08).

Social movements for climate justice also attach great importance to involving their audience on social media, for example, 'we do YouTube livestreams with scientists, celebrities, simply to get into conversation with other players. People can comment directly, people can give their opinion directly, people have the opportunity to get involved. (…) I also do surveys in Instagram stories. That's mega useful to enable a bit of participation so that people don't just click away. Most people like to click on their opinion and want to participate somehow' (Fridays for Future, local and national level, FFF01). Furthermore, climate activists appreciate that 'you might also come into contact with people who might have a different opinion, and that can be enriching, such an exchange of views. So even if they are contrary opinions, it is sometimes quite exciting to see a different point of view' (Health for Future, local level, HFF01). Likewise, the Schleswig-Holstein Farmers' Association also perceives it as 'a huge advantage that you meet people that you wouldn't meet otherwise, especially the critics. I think it's a huge advantage that we can do this today, that we can talk to each other. And I experience that again and again, that you can get in touch with each other about a criticism that you might have of each other, and that you can then move something forward together' (SHFA).

However, they avoid increasing the reach of actors pursuing different environmental policy goals which is why they 'do not interfere on other social media sites. We are purely on our channels. There, we also comment on topics, we also criticise Greenpeace or others, for example. We do all that, but we do it consciously on our channels' (SHFA). For the same reason, members of the Alternative for Germany also avoid commenting on the social media sites of their opponents and 'instead try to pull them in. If I make a post and they comment on my post in a negative way, what happens? Then many of my fans come and condemn this negative interpretation. Then many of their fans come and condemn it, and that builds up and you have an incredibly high reach because of that. That's the art of being so controversial that, of course, it's not criminally relevant but that you drag your opponents onto your own platform' (Alternative for Germany, state level, AFG01). In contrast to the other organisations, the German Combustion Engine Association actualises the interactive networking affordance only to a limited extent because 'we do not see ourselves as a discussion platform, but as an information platform. People are welcome to spread our posts on other sites and then we can discuss about it there. Because we can't afford this discussion platform. Then we would need a lot more administrators' (GCEA). Taken together, social movements for climate justice and the Schleswig-Holstein Farmers' Association actualise the interactive networking affordance in a constructive way to create networks that are able to bring about change. In contrast, the Alternative for Germany actualises the interactive networking affordance in a provocative way aiming at heated discussions on their channels to increase their reach.

A tension arises because the communication features provided by social media enable the affordance of interactive networking, but also the emergence of constraints such as hate speech and coordinated shitstorms. For example, 'people share articles via messengers. Quite often it's good stuff, but sometimes people hurl right-wing extremist agitation at you' (Fridays for Future, local and national level, FFF01). However, also actors pursuing different environmental policy goals are affected by hate speech, for example, a member of the Alternative for Germany expresses: 'It's amazing how many people feel called to attack you massively when you criticise Fridays for Future' (Alternative for Germany, state level, AFG01). The Alternative for Germany also feels unjustifiably excluded from environmental policy discussions on social media: ‘We are in any case always ready to talk about anything, but you are simply pre-judged. They say, no, we won't talk to you. (...) The whole story, yes, the AFG, they're just bullying around, they just want to cause stress, that's total nonsense’ (Alternative for Germany, local level, AFG03). For these reasons, a member of the Alternative for Germany on the national level does not see social media as a tool that can actually bring about change: ‘From time to time, critical comments come from people who have other opinions. But that's usually not at a level where you can discuss scientifically; it's all very vulgar. All in all, it has to be said that social media is self-promotion, to present one's position, one's work, in order to get re-elected. I don't believe that I have much of an effect on the outside world’ (Alternative for Germany, national level, AFG02).

A member of the national Fridays for Future press team points out that actors with other environmental policy goals attack them in a coordinated manner: ‘There are many networks that deliberately scatter one of our posts in their network to react angrily to this post. To create the impression that many people apparently don't like what's happening’ (Fridays for Future, local and national level, FFF04). The Schleswig-Holstein Farmers’ Association also has to deal with ‘cases in which farmers are directly affected by shitstorms [coordinated by vegan groups]. Then we also take over and continue the discussion on our page so that these people are rehabilitated. This happens to the point that we then bring veterinarians to the farm, that I film how he assesses the farm. And I then put that on our page so that this farm is rehabilitated’ (SHFA). The Board of the German Combustion Engine Association also confirms that ‘there are lots of forums about e-mobility, where people are called upon to go to our site and start a shitstorm’ (GCEA).

In some cases, the interviewees report a fear that personal attacks might not be limited to the social media space or that attacks in the physical world already happened. For example, in the east of Germany where social movements for climate justice do not have a high level of public acceptance, ‘it happens more often that when you get into a shitstorm on Twitter, things sometimes happen in the offline sphere as well’ (Fridays for Future, local and national level, FFF04). The social media manager of the Schleswig-Holstein Farmers’ Association also expresses ‘a fear that if people like that say something like that, what are they prepared to do? My wife is afraid that they will be at our front door at some point. And that already shows, the personal attacks, they also have a personal effect’ (SHFA). For the same reason, a member of the Alternative for Germany states: ‘I don't really reveal anything private about myself. I can't do that because otherwise I'd probably get visitors. If they knew where you live. There have also been cases of tar attacks. Or the car is burned down on the doorstep’ (Alternative for Germany, local level, AFG04).

To deal with the constraint of hate speech and coordinated shitstorms, a Fridays for Future manager on the national level, emphasises the importance of a professional response to these comments because ‘it’s a very different picture, if you just have hate comments than if you have hate comments plus the movement response to that.’ (Fridays for Future, national level, FFF08). Social movements for climate justice also restrict access to their Facebook and WhatsApp groups ‘to see if there aren't some AFG people in disguise who then just want to interfere in our groups to pass on their information and spread hate messages’ (Fridays for Future, local and national level, FFF01). Other than that, all interviewed organisations rather delete hate comments on their channels. For example, social movements for climate justice are checking ‘is this negative comment now the beginning of a constructive discussion or do I delete it’

(Fridays for Future, local level, FFF03). Similarly, the social media manager of the Schleswig-Holstein Farmers' Association has 'gotten into the habit of taking a breath when things get too bad and then either deleting the comments wholesale or not looking at all' (SHFA). The Board of the German Combustion Engine Association also states: 'We have rules of conduct on the site. And if someone violates it several times, we block them' (GCEA). Likewise, a social media manager of the Alternative for Germany explains: 'I look through my page and, if there are any comments among them that are somehow offensive, click. Will be deleted' (Alternative for Germany, local level, AFG03). In summary, all interviewed organisations have to deal with hate speech and coordinated shitstorms regardless of how they actualise the interactive networking affordance.

Discussion

In our study, we examined the tensions between social media affordances and constraints that arise from the interaction of actors pursuing different environmental policy goals. In doing so, we focused on the interaction between social movements advocating for radical climate action (i.e., Fridays for Future and their subgroups) and actors advocating for slower change to maintain economic stability (i.e., Alternative for Germany, Schleswig-Holstein Farmers' Association, German Combustion Engine Association). Thereby, we answer the call to investigate the influence of external stakeholders on organisational affordance actualisation (Burton-Jones & Volkoff, 2017; Karlsen et al., 2019; Sæbø et al., 2020). To date, there are only a few studies that have considered the influence of other actors on affordance actualisation (Sergeeva et al., 2013; Wang & Nandhakumar, 2016). For example, Sergeeva et al. (2013) found that users actualise affordances in different ways depending on the perceptions of other people who are present. Wang and Nandhakumar (2016) showed that other actors could facilitate affordance actualisation, for example, when IT staff resolves constraints for other employees. With our work, we contribute to this line of research by analysing three tensions between social media affordances and constraints that arise from the interaction between actors pursuing different environmental policy goals: (1) the affordance of informational education vs. the constraint of false information, ideology, and propaganda, (2) the affordance of emotional storytelling vs. the constraint of shadow bans and content deletion, and (3) the affordance of interactive networking vs. the constraint of hate speech and coordinated shitstorms.

Our results provide insights into how actors with different environmental policy goals actualise social media affordances depending on their goals (Strong et al., 2014). The most striking difference could be observed between social movements for climate justice and the Alternative for Germany. The affordance actualisations of social movements for climate justice are shaped by the goal of bringing about change. To achieve this goal, they actualise the emotional storytelling and interactive networking affordances in a positive way. For example, they manage to mobilise people by conveying a positive atmosphere at demos in Instagram videos. They also build a support network through positive comments and active involvement of their community, which they use to set trends on Twitter that are often picked up by the media. In contrast, members of the Alternative for Germany do not believe that social media activities can actually bring about change, and thus they rather pursue the goal of increasing their reach before elections. To achieve this goal, they actualise the same affordances as social movements for climate justice, but in a provocative way. For example, they exploit the anger of the public about radical actions by climate activists and sometimes formulate posts bordering on criminal relevance to gain attention. They also deliberately provoke heated discussions on their platforms to achieve a higher reach through the high number of interactions.

While all actors report actualising affordances that promote goal achievement, they also perceive constraints hindering them at goal achievement (Majchrzak & Markus, 2012). Social media constraints for collective action have also been identified in previous research (e.g., Tim et al., 2017; Comunello et al., 2016; Dumitrica & Felt, 2019), however, it is still unclear how constraints arise. In information systems research, it is heavily discussed whether affordances are embedded in IT artifacts or emerge in practice (e.g., Lanamäki et al., 2016; Stendal et al., 2016; Alshawmar, 2021). However, the debate on the ontological nature of constraints as the counterpart to affordances has not progressed to the same extent, yet. We found that the technological characteristics of social media platforms not only enable the actualisation of affordances, but also the perception of constraints (Leonardi, 2011). For example, the comment feature enables the actualisation of interactive networking, but also gives rise to the constraint of hate speech and coordinated shitstorms. However, we argue that not only the technological characteristics of social media platforms, but additionally the affordance actualisations of actors pursuing different environmental policy goals play a role in the emergence of constraints. Our study shows that constraints can be either (1) self-imposed by the manner of one's own affordance actualisations or (2) arise from the affordance actualisations of other actors pursuing different environmental policy goals.

An example for a self-imposed constraint would be the constraint of shadow bans and content deletion that arises mainly for the Alternative for Germany because of the way in which they themselves actualise the emotional storytelling affordance. Since some members actualise the emotional storytelling affordance by formulating provocative posts bordering on criminal relevance, they come under greater scrutiny from platform operators, who are legally obliged to delete content relevant to criminal law due to the Network Enforcement Act in Germany. This finding highlights the paradoxical effects of affordance actualisation (Ciriello et al., 2019; Majchrzak et al., 2013; Tim et al., 2017). While, for example, the actualisation of the emotional storytelling affordance in a provocative way can promote goal achievement (e.g., increasing attention and reach), this actualisation can also result in constraints that diminish these positive effects (e.g., reducing reach because of shadow bans and content deletion).

The constraint of false information, however, arises because actors with different environmental policy goals actualise the informational education affordance. For example, social movements for climate justice claim to actualise the informational education affordance by sharing fact-based information, but because of their different views, the Alternative for Germany perceives their informational activities as attempts to share false information. It needs to be mentioned here that we as authors cannot judge which actors truly spread false information on social media, however, for the perception of constraint we deemed the subjective experience of the participants as relevant.

The constraint of hate speech and coordinated shitstorms is an example of a constraint that is partly self-imposed and partly caused by the affordance actualisations of actors pursuing different environmental policy goals. For example, the constraint arises for the Alternative for Germany, which deliberately provokes heated discussions on social media when actualising the interactive networking affordance, increasing the likelihood that discussions will degenerate into an exchange of insults and threats. However, the same constraint is also perceived by social movements for climate justice and the Schleswig-Holstein Farmers' Association, although they actualise the interactive networking affordance in a positive way. This happens because actors with other environmental policy goals actualise the interactive networking affordance in a negative way, for example by coordinating shitstorms (e.g., right-wing populists, vegan groups, electrical car enthusiasts).

The affordance actualisations of social movements for climate justice and organisations pursuing different environmental policy goals include the key elements of paradoxes, namely contradiction and interdependence (Smith & Lewis, 2011). On the one hand, actors perceive constraints due to the affordance actualisation from other actors pursuing different goals. On the other hand, actors who actualise, for example, the interactive networking affordance in a provocative way are also dependent on actors pursuing different environmental policy goals. If the latter would not be tempted to engage in heated discussions, actors employing a provocative way of affordance actualisation would not achieve the desired result of a higher reach.

To resolve paradoxical tensions between affordances and constraints, we found evidence of both avoidance and confrontation strategies (Jarvenpaa & Lang, 2005). For example, the German Combustion Engine Association refrains from actualising the interactive networking affordance because they have not enough administrators to deal with the constraint of hate speech and coordinated shitstorms. This confirms that the perception of constraints can prevent the actualisation of desired action potentials and the achievement of associated outcomes (Bernhard et al., 2013; Bobsin et al., 2019; Ens et al., 2018; Goh et al., 2011; Leonardi, 2011; Majchrzak & Markus, 2012). Another example would be that members of the Alternative for Germany started to actualise affordances on Telegram where especially the constraint of shadow bans and content deletion is perceived to a lesser extent. This shows that users adapt their social media use based on platform-specific perceptions of affordances and constraints (Comunello et al., 2016). On the other hand, actors can recognise new ways to actualise affordances over time to resolve tensions (Grgecic, Holten, & Rosenkranz, 2015; Leonardi, 2011; Strong et al., 2014). An example is the social media manager of the Schleswig-Holstein Farmers' Association who recognised the potential of videos to rehabilitate farmers after a shitstorm coordinated by vegan groups.

Theoretical Contribution

Our study offers three main contributions to the current body of knowledge in information systems research. First, we propose two paths that can lead to the perception of social media constraints in the context of collective action: (1) imposing constraints on oneself through one's own affordance actualisations and (2) emerging through the affordance actualisations of other actors pursuing different goals on the same platform. Thereby, we extend the discussion on the ontological nature of affordances in information systems research by focusing on constraints as their counterparts (e.g., Lanamäki et al., 2016; Stendal et al., 2016; Alshawmar, 2021).

Second, we extend research on paradoxical tensions (Ciriello et al., 2019; Jarvenpaa & Lang, 2005; Majchrzak et al., 2013; Smith & Lewis, 2011; Tim et al., 2017) by analysing tensions between social media affordances and constraints arising from the interactions of actors pursuing different environmental goals. We highlight the fact that affordance actualisation on the part of social movements can lead to the perception of constraints for actors pursuing different environmental policy goals and vice versa. At the same time, the success of affordance actualisations can depend on the reactions of actors pursuing different environmental policy goals.

Third, we examined how actors adapted the way in which they actualise affordances to resolve paradoxical tensions (Jarvenpaa & Lang, 2005). We found that actors can either refrain from affordance actualisation to avoid the associated constraints or recognise new ways of affordance actualisation to diminish the negative effects of constraints. Thereby, we contribute to the scant body of information systems research on the influence of other actors on affordance actualisation (Sergeeva et al., 2013; Wang & Nandhakumar, 2016).

Practical Implications

Our research also has practical implications for actors pursuing different environmental policy goals and social media providers. First, social media providers can learn, from the identified constraints, how they could support social change through the design of their platforms. Providers could improve the training of their employees responsible for evaluating flagged posts to ensure that content relevant to criminal law is deleted more quickly (e.g., hate speech, incitement of the masses). Such trainings should also ensure that actors pursuing different environmental policy goals are fairly treated independent of their political views. Furthermore, social media providers could diminish constraints by redesigning their recommendation algorithms in a way that the negative actualisation of emotional storytelling and provocative actualisation of interactive networking are less effective.

Second, the findings provide social movements and actors pursuing different environmental policy goals with insights into how to effectively use social media to bring about change. Social movements for climate justice should not get tempted to respond to provocative posts and comments by actors pursuing different environmental policy goals to reduce the effectiveness of such affordance actualisations. For actors pursuing different environmental policy goals, actualising affordances in a more positive way could help to diminish self-imposed constraints such as shadow bans and content deletion.

Conclusion

In this study, we examined the social media use of social movements for climate justice through the lens of technology affordances and constraints theory (Majchrzak & Markus, 2012). We conducted 30 semi-structured interviews with climate activists who managed social media accounts at the local, state, or national levels. Furthermore, we interviewed six members of organisations pursuing different environmental policy goals. This allowed us to analyse tensions between social media affordances and constraints arising from the interaction with actors pursuing different goals on the same platforms. Thus, our results contribute to a better understanding of effective social media use for collective action in the field of information systems.

Our research has some limitations, which also point to avenues for future research. The study focused on highly organised climate movements, meaning that the transferability of the findings to other types of movements may be limited. Furthermore, we interviewed only German activists and were only able to interview a smaller number of members from organisations with different environmental policy goals. Some interviewees in our study mentioned that the movement plans to expand its social media use to TikTok and LinkedIn, which points to further platforms that could become relevant for collective action. In terms of affordances and constraints, this study suggests that social media use by social movements should not be considered in isolation but, rather, that other actors can influence the actualisation process. Therefore, a more detailed examination of the positive and negative influences of other actors, such as counter-groups, politicians, and journalists, on the actualisation process of social movements remains a significant research gap in information systems research.

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List of Tables

Table 1. Overview about Social Media Affordances for Collective Action

Social media affordances for collective action identified in previous research	**References**
Information validation, information supplementation, perpetual self-updating, perpetual mass-updating, self-reportage, monitoring and influencing, self-organisation, interactive communication, self-presentation	(Harindranath et al., 2015)
Gathering relevant political information, sharing relevant political information, expressing opinions, discuss controversial topics, seeking diverse opinions, exceeding boundaries of close ties, seek for network homogeneity	(Comunello et al., 2016)
Enforcing transparency, enhancing accountability, enacting public scrutiny, distributed collaboration, agenda setting, framing, recruiting/enrolling participants, mobilising resources	(Zheng and Yu, 2016)
Information democratisation, emergent organising, network-informed associating	(Tim et al., 2017)
Sharing personal stories, coordination of massive, staged acts, collective framing and narrative construction	(Khazraee & Novak, 2018)
Communication affordance, membership affordance, character movement affordance	(McKenna, 2019)
Circulating information, crossing boundaries, adapting rules and processes, making decisions collectively, (de-)structuring the community, delimiting actions, connecting members, triggering actions	(Sæbø et al., 2020)

Table 2. Overview about Social Media Constraints for Collective Action

Social media constraints for collective action identified in previous research	References
Filter bubbles, information overload, dissemination of misinformation	(Tim et al., 2017)
Information overload, restricted length of postings, privacy concerns, lack of knowledge and skills	(Comunello et al., 2016)
Technical barriers (predefined network logics and algorithms, filter bubbles), interactional barriers (dissemination of misinformation, personal barriers (emotional strain and career risks)	(Dumitrica & Felt, 2019)

Table 3. Overview of Interviewees (Social Movements for Climate Justice)

Sample characteristics		N (in %)
Gender		
	Female	15 (50%)
	Male	15 (50%)
Age		
	< 20 years	6 (20%)
	20 years–30 years	21 (70%)
	> 30 years	3 (10%)
Movement affiliation		
	Fridays for Future	25 (83%)
	Health for Future	2 (7%)
	Students for Future	1 (3%)
	Scientists for Future	1 (3%)
	Vegans for Future	1 (3%)
Level of social media management		
	Social media manager of a local group	25 (83%)
	Member of a state social media team	3 (10%)
	Member of the national social media team	7 (23%)
Social media platforms managed		
	Instagram	29 (97%)
	Facebook	29 (97%)
	Twitter	23 (77%)
	WhatsApp	20 (67%)
	Telegram	12 (40%)

Table 4. Overview of Interviewees (Organisations with Different Environmental Policy Goals).

ID	Gender	Age	Affiliation	Social media platforms managed
AFG01	Male	53	Member of the Bavarian State Parliament (Alternative for Germany)	Facebook, Twitter, YouTube, Telegram
AFG02	Male	59	Member of the German Federal Parliament (Alternative for Germany)	Instagram, Facebook, Twitter, WhatsApp, Telegram
AFG03	Male	54	Board of the Alternative for Germany District Association Northwest Mecklenburg	Facebook
AFG04	Male	47	Board of the Alternative for Germany District Association Wolfsburg	Facebook, Twitter, Telegram
SHFA	Male	55	Member of the Schleswig-Holstein Farmers' Association	Instagram, Facebook, Twitter, YouTube, WhatsApp
GCEA	Male	52	Board of the German Combustion Engine Association	Instagram, Facebook, WhatsApp

Table 5. Interview Guide

Concept	Example Questions
Socio-demographics	Please introduce yourself! How old are you? What gender do you feel you belong to? How do you get involved within your organisation?
Social media use	What goals are you pursuing with the use of social media for your organisation? What social media platforms do you use? For what purposes do you use the individual platforms?
Actualised affordances	We presented a list of social media features (see Appendix B) and asked the following questions related to these features: What possibilities for action do these features offer you that can help you achieve organisational goals? What is the outcome of this use for your organisation?
Perceived constraints	What disadvantages or limitations do you see in each platform? Are there opportunities for action that you would have expected to find on the platforms you use but don't? If so, what are they?
Use of multiple social media platforms	Why are you using multiple social media platforms? To what extent are your perceived opportunities for action and limitations a reason you use these different platforms?
Impact of constraints on affordance actualisation	How do these perceived limitations affect your usage behavior? What impact do the actions of other users with different environmental policy goals have on your usage behavior? How do you respond to the activities of organisations pursuing different environmental policy goals or users with contrary opinions?

Table 6. Implementation of the Active Categorisation Framework for Theory Development

Analytical move	Implementation in our study
Asking questions	While reading the interview transcripts, we approached the material with questions such as ‘Which affordances do social movements for climate justice and actors pursuing different environmental policy goals actualise on social media? Which constraints do social movements for climate justice and actors pursuing different environmental policy goals actualise on social media? How are affordance actualisations related to the perception of constraints?’
Focusing on puzzles	We focused on the aspects of the transcripts that were most surprising to us. An example would be the paradox that constraints can arise from affordance actualisation because at first glance it is not intuitive that the realisation of action potentials might lead to the perception of constraints.
Dropping categories	Guided by the first two analytical moves, we decided to drop affordance actualisation and constraint categories that did not gain theoretical traction. An example would be that several participants mentioned technical constraints such as feature limitations. We considered it as common sense that the technological characteristics of social media platforms give rise to constraints. Also, we dropped affordance actualisation categories that did not have any relationship to the emergence of constraints because no tensions could be discussed.
Merging categories	We merged categories of constraints that were related to the same affordance actualisations, and vice versa. For example, the constraints of shadow bans and content deletions were merged because they both arise due to the actualisation of the emotional storytelling affordance.
Splitting categories	We split categories of constraints that were related to different affordance actualisations, and vice versa. For example, we split the constraints of false information and hate speech because these were related to the actualisation of different affordances (informational education and emotional storytelling).

Relating or contrasting categories	By comparing affordance actualisation and constraint categories with each other, we identified paradoxical tensions between them. For example, we found that the actualisation of the emotional storytelling affordance results in positive outcomes (i.e., increased reach) but can also give rise to the constraint of shadow bans and content deletion resulting in the opposite outcome (i.e., reduced reach).
Sequencing categories	This analytical move can be used to temporally organise categories, however, we found temporal sequences not to be relevant in our context.
Developing or dropping working hypotheses	By iterating through the data, we constantly questioned and refined our working hypotheses. For example, we assumed that only the affordance actualisations of actors pursuing different environmental policy goals give rise to constraints. However, we recognised that constraints can also be self-imposed by the manner of one's own affordance actualisations.

Appendix A: Coding Guide

Category	Description	Anchor Example
Main Category: Actualised Social Media Affordances		
Informational education	Social media are used to inform and educate the public about the climate crisis, provide information about demonstrations, and correct false information spread by other actors. Scientific sources are added to informational posts to back up the statements.	'One of the biggest goals is education, information about the climate crisis. There has been far too little information work in this direction in recent years. For that, social media is a huge platform we can use, apart from demos' (FFF08).
Emotional storytelling	Social media are used to convey either positive or negative emotions. On the one side, this affordance includes the strategic use of image and video content to convey a positive atmosphere during demos and posting funny content to create a feeling of cohesion. On the other side, this affordance includes the use of sensational headlines and controversial images fuelling the anger of the public.	*Positive emotions:* 'Videos and photos are generally content that arouse emotions. So, it's a lot of calculation that you create a reference to certain topics and try to post beautiful pictures. To make the whole thing a bit more appealing to people' (FFF01). *Negative emotions:* 'We won't spread any lies, but there are things about this topic that have an emotional impact. And of course, we use them, otherwise we would never have reached such high numbers of followers' (GCEA).
Interactive networking	Social media are used to interact with other users either in a supportive or provocative way. On the one side, this affordance includes supporting like-	*Supportive interaction:* 'What I do is that I go to the accounts of Fridays for Future activists, for example, and that I then comment "Great

	minded individuals and organisations (e.g., via likes, comments, shares), involving the audience (e.g., via surveys in Instagram stories), collaboratively setting Twitter trends, and exchanging opinions with users outside the own filter bubble in a constructive way. On the other side, this affordance includes provoking heated discussions in the comment sections on one's own page to increase the number of interactions.	page" to support them' (Health for Future, local level, HFF01). *Provocative interaction:* 'If I make a post and they comment on my post in a negative way, what happens? Then many of my fans come and condemn this negative interpretation. Then many of their fans come and condemn it, and that builds up and you have an incredibly high reach' (AFG01).
Main Category: Perceived Social Media Constraints		
False information, ideology, and propaganda	Actors perceive that other users spread false information about the climate crisis and misleading statistics. Also, actors perceive that other users do not disseminate facts but ideologies and propaganda to influence people.	'It is a noble cause to save the climate, but then they must also back up with facts that mankind is responsible for the entire global warming. So far, no one has succeeded in doing that' (AFG03).
Shadow bans and content deletion	Actors perceive that other users are unjustifiably flagging their content as violating community standards. As a result, actors receive a shadow ban (content is still available but not recommended by algorithms anymore) or content is deleted by platform providers.	'Social networks are tightening their rules more and more. And our opponents are taking advantage of that. Anything that even comes close to not being verified is reported. And the problem is not so much the blocking, but the loss of reach' (AFG04).
Hate speech and coordinated	Actors perceive that other users confront them with hate speech via direct messages and comments.	'It's amazing how many people feel called to attack you massively when you criticize Fridays for Future'

shitstorms	Furthermore, actors perceive that other users pursuing different environmental policy goals coordinate shitstorms.	(AFG01).

Appendix B: Features of Social Media and Instant Messengers in Germany

Platform	Features (during first data collection phase in 2020)	Features (during second data collection phase in 2022)
Instagram	Profile, home feed, image posts, video posts, IGTV, reels, stories, comments, likes, messenger, discovery feed, search, livestream, follow, save posts, forward posts via messenger	New: Stronger focus on videos (especially reels), co-authorship, longer stories, story likes, avatars, Instagram shopping
Facebook	Profile, news feed, Facebook wall, search, friends, messenger, groups, events, status updates, livestream, stories, reactions, share posts, comments	New: Reels, distinction between home feed tab (showing personalised recommendations) and chronological feed tab (showing latest posts from friends and favourite pages)
Twitter	Profile, tweets, retweets, favourites (likes), replies, follow, timeline, direct messages, search	New: Topics, mixed media tweets (including up to four different media types), Twitter circle (share tweets only with selected users)
YouTube	Channel, videos, search, subscribe, rate (thumbs up/down), comments	New: Shorts (similar to reels), number of thumbs down not visible anymore
WhatsApp	Profile image, status, individual and group chats (up to 256 users), (video) calls, stories, voice messages, share (photos, videos, documents), one-time-view photos and videos, end-to-end encryption	New: Status visibility settings, reactions
Telegram	Profile image, status, individual and group chats (up to 200,000 users), public and private broadcasting channels (unlimited number of users), secret chats (end-to-end encrypted),	New: Interactive emoji reactions, group membership requests, verifications for groups, channels, and bots

	self-destructing messages, bots, (video) calls, stories, voice messages, search, edit messages, share (photos, videos, documents)

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