On the interaction between affective and cognitive processes in decisions under risk: Underlying behavioral, neural, and neuroendocrine correlates

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Hiermit versichere ich, dass die vorgelegte Dissertation gemäß §9 der Promotionsordnung der Fakultät für Ingenieurwissenschaften der Universität Duisburg-Essen vom 9. Juni 2009 eine selbstständig durchgeführte und eigenständig verfasste Forschungsleistung darstellt und ich keine anderen als die angegebenen Hilfsmittel und Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus anderen Schriften entnommen sind, habe ich als solche kenntlich gemacht. Die Arbeit hat weder in gleicher noch in ähnlicher Form einem anderen Prüfungsausschuss vorgelegen

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Publication Notes

At the date of the submission of this thesis the three studies were within the following states of the publication process:

Study 1, pp. 81 - 100:
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Study 2, pp. 101 - 115:
Gathmann, B., Pawlikowski, M., Schöler, T., & Brand, M. (2014) Performing a secondary executive task with affective stimuli interferes with decision making under risk conditions. *Cognitive Processing*, 15, 113–126.
The publication is available at link.springer.com/article/10.1007/s10339-013-0584-y

Study 3, pp. 116 - 127:
Gathmann, B., Schiebener, J., Schöler, T., & Brand, M. (in revision). Monitoring, a key function of dual tasking: Decision making under risk and a parallel executive task.

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List of abbreviations

ACC	anterior cingulate cortex
ANCOVA	analysis of covariance
ANOVA	analysis of variance
aPFC	anterior prefrontal cortex
BA	Brodmann area
BART	Balloon Analogue Risk Task
BOLD	blood oxygen level dependent
BST	Balanced Switching Task
CFI	comparative fit index
CG	Cold Pressor Test
CS	contention scheduling
dlPFC	dorsolateral prefrontal cortex
EEG	electroencephalogram
EPIC	executive-process interactive control
ERP	event-related brain potential
fMRI	functional magnetic resonance imaging
FOV	field of view
GDT	Game of Dice Task
GLM	general linear modelling
HPA-axis	hypothalamic pituitary adrenal axis
IGT	Iowa Gambling Task
LPS	Leistungsprüfsystem
MCST	Modified Card Sorting Test
MNI	Montreal Neurological Institute
MPRAGE	magnetization-prepared rapid gradient-echo
MRI	magnetic resonance imaging
OFC	orbitofrontal cortex
PAG-task	Probability Associated Gambling task
PANAS	Positive and Negative Affect Schedule
PFC	prefrontal cortex
RCZ	rostral cingulate zone
SAM-system	sympathetic adrenomedullary system
SAS	supervisory attentional system
SCR	skin conductance response
SEM	structural equation modelling
SG	stress group
SPM	statistical parametric mapping
SRMR	standardized root mean square residual

STAI	State Trait Anxiety Inventory
TE	echo time
TLI	Tucker-Lewis Index
TMT	Trail Making Test
TOH/TOL	Tower of Hanoi/Tower of London
TR	repetition time
TSST	Trier Social Stress Test
vmPFC	ventromedial prefrontal cortex
WCST	Wisconsin Card Sorting Test

1. General Abstract

The present thesis taps into the field of neuropsychological decision-making research. In this field it is common to distinguish between decisions under ambiguity and decisions under risk. In situations under ambiguity the decision maker has no information about the consequences and their probabilities of occurrence, which is why she/he has to rely on her/his intuitions and experiences with the situation (e.g., Bechara, Damasio, Damasio, & Anderson, 1994). In contrast, in situations under risk information about consequences and probabilities is given and the decider can process them to make a decision (e.g., Brand, Labudda, & Markowitsch, 2006). In their model of decision making under risk, Brand and colleagues (2006) postulated the involvement of cognitive and affective processes. Over the years, several studies supported this assumption. However, little was known about the interaction between the underlying cognitive and affective processes and the associated neural correlates. The research for this thesis was conducted to fill this gap. The first study aimed to investigate the neural correlates of the interaction between decision making, additional cognitive demand, and stress. It was found that stress appears to trigger a shift from serial to parallel processing brain regions to prevent decision-making performance from decreasing, supporting the assumptions made in previous studies (Pabst, Schoofs, Pawlikowski, Brand, & Wolf, 2013; Plessow, Schade, Kirschbaum, & Fischer, 2012). The second study concentrated on the possibility that cognitive functions might have an important role in facilitating decision making in situations when both processing routes (affective and cognitive) are demanded at the same time. The results revealed that although affective stimuli (especially those of positive valence) interfere with the decision-making performance, participants with superior executive functioning seem to be unaffected and were still able to decide advantageously. In contrast, participants with inferior executive functions were affected and showed disadvantageous decision making. In the third study the focus of investigation was which subcomponents of executive functioning might be involved in decision-making situations with additional cognitive demand. The findings suggest the involvement of higher-level executive functions and lower-level executive functions in decision making when the cognitive route is additionally loaded by another cognitive demanding task simultaneously. In order to measure the additional cognitive load, a dual task consisting of a decision-making task and an additional cognitive task was used in each study. In conclusion, the findings suggest that in decision-making situations with additional cognitive and affective demand, underlying affective and cognitive processes interact in a way that they prevent a decrease of decision-making performance. The findings and the therefrom derived assumptions are discussed in detail and perspectives for future outcomes are given.

2. General introduction

Everyday life consists of many challenging situations and demands. People have to make decisions constantly. Some decisions are easy to make and rather random, for instance when to drink from a cup of tea next to you on the table. Most of these decisions can easily be done while doing other cognitive, even challenging things simultaneously. For example, deciding to take a sip of tea while writing a demanding essay will easily be done. However, there are decisions that need more cognitive resources, need to be thought through carefully, for example to decide which job offer to take or where to invest money. Decisions of this nature are hardly performed in parallel with other cognitive, challenging assignments. Moreover, a situation provoking a decision can be affective-hued, for example the decision to get married. Others have to be done under stressful conditions. An extreme example would be the actions of a doctor in an operating room that can leave to a decision about life or death. These are only a few examples demonstrating the importance and variety of decisions and decision situations in human everyday life. Hence, it is not surprising that decision making is also a topic in the field of research.

Today, there are many different research fields investigating the topic of decision making. In total, they can be assigned to one of two theoretical approaches: the *normative/prescriptive* and the *positive/descriptive* approach (Kleindorfer, Kunreuther, & Schoemaker, 1993). The normative approach engages in explaining the best decision-making process by trying to maximize the optimal decision for individuals, organizations, and public relations. In contrast, descriptive approaches investigate the actual decision-making process. Here, it is of interest how humans make their decisions, how they process and use information and which limitations and systematical biases influences the decision-making process (Kleindorfer, et al., 1993). Due to the fact that decision situations differ in the amount of information offered, decisions can be placed on a continuum from *complete ignorance* on the one side of the continuum (where no information, not even about the possible outcomes of a decision, are known) to *certainty* of the other side of the continuum (where it is known that only one deterministic outcome will result). Between those endpoints lay *uncertainty* or *ambiguity* (where the outcome may be known, but the probabilities of occurrence are not precisely specified) and *risk* (where the outcome distribution is specified) (Weber & Johnson, 2009).

To the field of descriptive research belongs the neuropsychological approach of decision-making research. Neuropsychological decision-making research tries to identify the underlying neural, cognitive, and affective correlates of decision making (e.g., Brand, et al., 2006; A. R. Damasio, Everitt, & Bishop, 1996; Kahneman, 2003). In this field, it is common to distinguish between decisions under ambiguity and decisions under risk. Decision making in ambiguous situations is characterized by the fact that even though the person making the decision may have information about the possible consequences of a decision, he/she has no information about their probability of occurrence. The person has to make a decision by relying on hunches and guesses. He/she has to trust in his/her *gut feelings* concerning the decision (Bechara, et al., 1994; Bechara, Damasio, Tranel, & Damasio, 1997). This is mostly true for personal and social decisions. For example, the decision to start a relationship with a significant other is usually made because of feelings and not because of rational deliberation. To start a relationship may have the consequence to live happily ever after or to be forever miserable, but before making the decision to start a relationship or not, there is no information about how likely one or the other consequence will occur. However, based on her/his feelings regarding the significant other the

person will still be able to make a decision. In contrast, in decisions under risk the consequences are well known and the situation provides information about the probabilities of occurrence (Brand, et al., 2006). For example, in case of prescription for a certain medication the patient information leaflet states the probabilities of diverse side effects. Based on this information the patient can deliberate whether he/she is willing to take this medicine.

The present thesis is located in the field of neuropsychological decision-making research and should contribute to broaden the knowledge of the underlying neural, cognitive, and affective processes of decision making. Therefore, a theoretical background about neuropsychological decision making under ambiguity and risk will be given (see chapters 3 to 3.5), whereby the focus of the thesis is on decision making under risk. Since, decision making under risk conditions involves affective and cognitive processes (Brand, et al., 2006) the interaction between these processes will be of special interest. Several studies already demonstrated that a simultaneous demand on either the cognitive route, for example by an additional executive task (Starcke, Pawlikowski, Wolf, Altstötter-Gleich, & Brand, 2011) or on the affective route, for example due to a stressful situation in which a decision has to be made (Starcke, Wolf, Markowitsch, & Brand, 2008), leads to diminished decision-making performance. Indeed, real life decision situations appear to be more complex by demanding both routes while making a decision additionally. For example: A student is on his/her way to a very important exam at the university. This situation itself might be stressful. Additionally, the train he/she wanted to take is canceled. The student needs to reschedule the train, while simultaneously deciding if it will still be possible to arrive in time or if it might be better to skip the exam and retake it another time. In respect of the findings above it appears obvious to assume that an additional demand on both routes would lead to an even increased impairment of decision-making performance. However, a recent study displayed that in a decision situation in which participants were stressed (load on the affective route) and had to perform an additional executive task simultaneously (load on the cognitive route); the decision-making performance did not decrease. Instead, these participants demonstrated analogues decision-making performance to non-stressed control participants making a decision without additional cognitive demand (Pabst, Schoofs, et al., 2013). This appeared to be a paradoxical finding, which the authors explained by a possible cognitive processing shift from serial processing to parallel processing, triggered by stress (for a detailed discussion see section 3.4.4). Nevertheless, this was the first study investigating the interaction between additional cognitive demand and stress in decision making under risk. To broaden the knowledge about such interaction and the underlying neural correlates in particular, the first study of the current thesis was conducted. Due to the fact that some studies gave first hints in the direction that cognitive functions seem to moderate the influence of affective processes in decision making (e.g., Brand, Laier, Pawlikowski, & Markowitsch, 2009; Pabst, Schoofs, et al., 2013), the second study investigated whether cognitive functions could prevent decision-making performance from decreasing when both processing routes (affective and cognitive) are demanded. The third study was conducted to get a better understanding of the cognitive functions involved in situations in which a person needs to make a decision while performing an additional cognitive task simultaneously. In order to measure the additional cognitive load, a dual-task consisting of a decision-making tasks and an additional cognitive task was used in each study.

The present thesis is structured as follows: At first a theoretical overview about decision making under ambiguity and risk (chapter 3), the underlying affective (section 3.1) and cognitive processes (section 3.2) as well as the underlying neural correlates (section 3.3) will be given. This is followed by a theoretical background of situational influences on decision-making performance (section 3.4), such as additional cognitive demand

(section 3.4.1), affective influences (section 3.4.2), stress (section 3.4.3), and the interaction between them (section 3.4.4). The theoretical part closes with a conclusion from theoretical background. Thereafter, the reports of the three studies are presented (chapter 4 to 6). Each of the reports consists of a separate theoretical introduction, in which the core notions for the specific study and the consequent hypotheses are laid out. At this point it has to be mentioned that each research report is supposed to be readable as an independent manuscript. Accordingly, some information which has already been addressed in the general theoretical background will again be subject of the theoretical introduction. Furthermore, each study ends with a separate discussion of the results. However, at some points the studies are adjusted to provide the readability of the thesis. Therefore, the studies may slightly differ from the original versions of the manuscripts (see publication notes). After the third study the main results of the three studies are summarized (section 7.1) and will be discussed in the light of the current theoretical and empirical findings and an impulse for future studies will be suggested (section 7.2 and 7.3).

3. Theoretical background: Decision making from a neuropsychological perspective

In neuropsychological decision-making research it is distinguished between decisions under ambiguity and decisions under risk. While in ambiguous decisions no or less information is given and the decider has to rely on hunches and guesses to make a decision (Bechara, et al., 1994; Bechara, et al., 1997), in decisions under risk the decider is provided with probabilities of possible outcomes of a decision and might calculate which decision will be best (Brand, et al., 2006). Over the years of research two decision-making models, describing the underlying processes of either decision making under ambiguity or decision making under risk, were postulated.

In their model of decision making under ambiguity (see Figure 1) Bechara and colleagues (1997) assumed that the sensory representation of a decision situation leads to two parallel, but at some points also interacting chains of events.

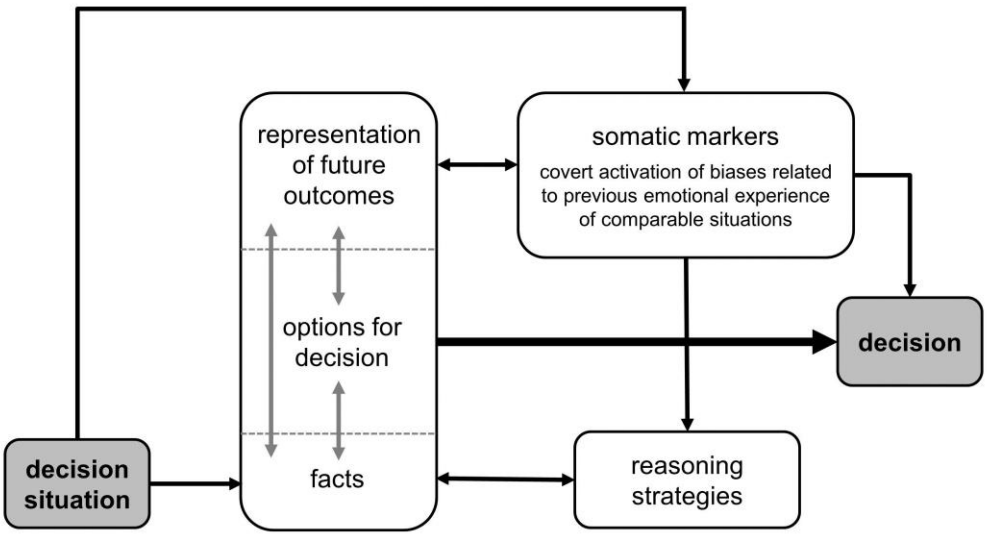

Figure 1 The model of decision making under ambiguity adapted from Bechara and colleagues (1997).

In one chain the sensory representation of the situation activates "neural systems [ventromedial prefrontal cortex (vmPFC) that activates further regions, see section 3.1.2] that hold non-declarative dispositional knowledge related to the individual's previous affective experience of similar conditions" (Bechara, et al., 1997, p. 1294). The subsequent non-conscious signals from the body or their mental representation (*somatic markers*, see section 3.1.2) act as covert biases on cognitive processing (e.g., reasoning or evaluation of facts etc.) or on the decision itself. In the other chain of events the representation of the decision situation leads to an overt recall of pertinent facts (e.g., options for decisions or associated future outcome) and to the application of reasoning strategies. Bechara and colleagues assumed that the activation of the covert biases precedes overt reasoning and thereby may support the reasoning process underlying conscious decision making.

Inspired by the model of decision making under ambiguity Brand and colleagues (2006) postulated a model of decision making under risk (see Figure 2).

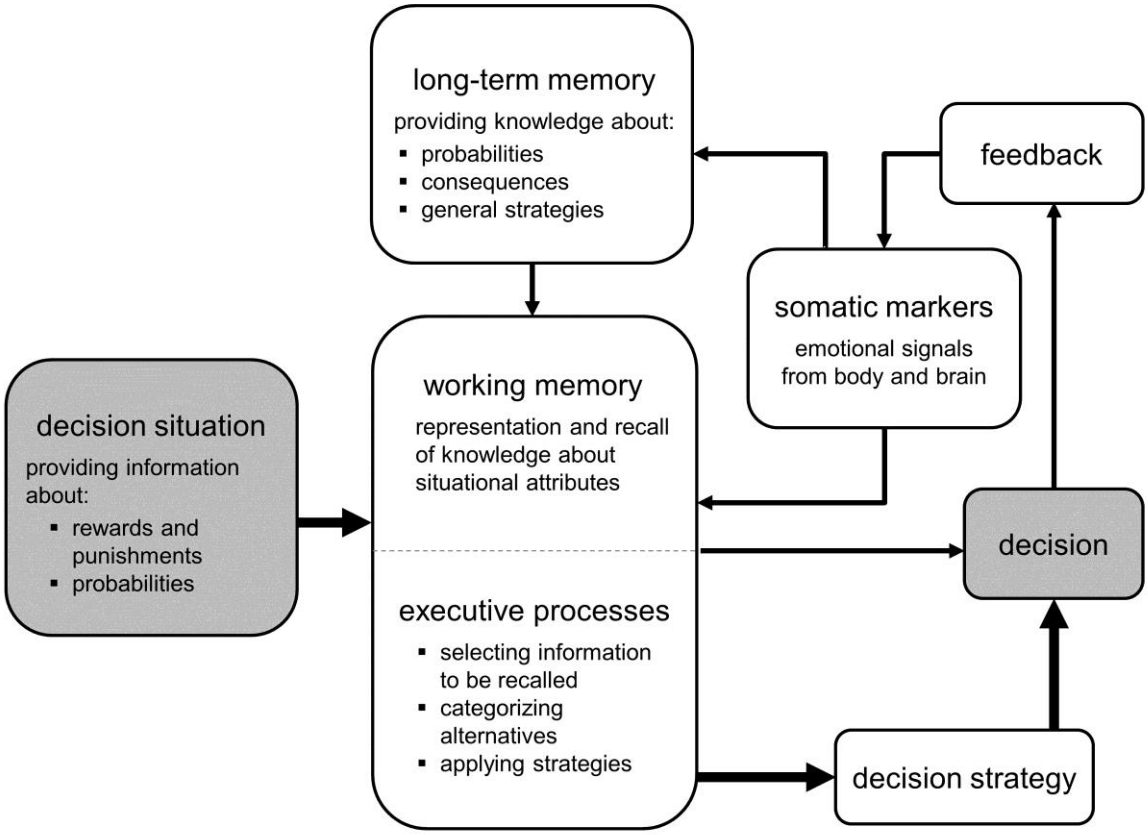

Figure 2 The model of decision making under risk modified from Brand and colleagues (2006).

The authors assumed that the various features of a decision situation are represented in working memory. In relation to these situational features information from long-term memory (e.g., knowledge about probabilities, previous experiences with comparable decision situations, and problem solving strategies) is recalled. This recall of information is triggered and controlled by *executive functions* (e.g., categorization, monitoring, and cognitive flexibility; for detailed information about executive functions see sections 3.2). The

combination of current, situational and recalled information occurs in working memory and results in a current decision strategy that guides the decision. At this point, the covert biasing signals (somatic markers, see section 3.1.2) can be involved in the selection process of a decision-making strategy. However, similar to decision making under ambiguity the biasing signals may also guide the decision directly without applying a specific strategy. The decision itself is followed by a positive or negative feedback evoking biasing signals that in combination can be stored in long-term memory or as a representation of the biasing signals. Moreover, Brand and colleagues assumed that for decisions under risk the cognitive route, i.e., without usage of the feedback and biasing signals, can lead to an advantageous decision alone. But the reliance on the biasing signals associated with affective experiences will also lead to a decision, resulting in the assumption of two parallel but interacting ways: an affective and a cognitive route (Brand, et al., 2006).

In order to operationalize decision-making situations under ambiguity and risk, neuropsychological research often uses decision-making tasks. Those tasks differ in the amount of information given concerning rules, potential outcomes like gains and losses, and the possibility to calculate the probabilities for a gain/loss. Ranging from no information about gain and losses and no possibility to calculate the probabilities (Iowa Gambling Task, IGT; Bechara, et al., 1994), to a gambling task with stable rules, amounts of gain and losses, and probabilities (Game of Dice Task, GDT; Brand, Fujiwara, et al., 2005). In between are ranked: the Balloon Analogue Risk Task (BART; Lejuez et al., 2002) that provides more information about the amounts for gain and losses than the IGT, but still offers no possibility to calculate the probabilities; followed by the Cambridge Gamble Task (CGT; Rogers, Everitt, et al., 1999) and the Probability Associated Gambling task (PAG-task; Sinz, Zamarian, Benke, Wenning, & Delazer, 2008; Zamarian, Sinz, Bonatti, Gamboz, & Delazer, 2008) that both provide changing probabilities and amounts in each trial. While the IGT taps into the field of ambiguity and thus studies using this task will be discussed in sections of decision making under ambiguity (sections: 3.1.2.1, 3.2.2.1, 3.4.1.4.1, 3.4.2.2.1, and 3.4.3.3.1) all other tasks display a certain amount of risk and studies using these tasks will be addressed in the sections of decision making under risk (sections: 3.1.2.2, 3.2.2.2, 3.4.1.4.2, 3.4.2.2.2, and 3.4.3.3.2). Table 1 gives an overview about the five commonly used decision-making tasks and displays the layout, the rules, the information given in each task, the information not known by the participants, and the measures used to evaluate the decision-making performance.

Table 1 Overview about five commonly used neuropsychological decision-making tasks.

Decision-making tasks				
IGT	**BART**	**CGT**	**PAG-Task**	**GDT**
Layout				
Four decks of undisclosed cards	Balloon and a balloon pump	Ten red or blue boxes and a hidden yellow token	24 red and blue cubes	Dice cup and a single virtual die
Aim				
Maximization of starting capital by choosing one card of the decks per trial	Maximization of starting capital by pumping up a simulated balloon	Maximization of starting capital by betting a certain percentage of the capital on which box will reveal a yellow token	Maximization of starting capital by deciding to gamble in a lottery or to take a fixed amount of loss/gain	Maximization of starting capital by betting which number will be thrown next
Given rules and information				
Starting capital of $2,000 Each card which participants have to choose leads to a gain, sometimes additionally to a delayed loss which is added or subtracted from the displayed starting capital and accompanied by a happy or sad smiley face Participants can switch between the decks each trial and are told that some decks are better than others	No starting capital Participants earn five cents each time they decide to pump up a balloon which is added to the temporary amount of money displayed on the screen; they are presented with 90 balloons and the explosion point varies across balloons Participants can decide how many times they want to pump up the balloon: Either they stop in time and collect the earned money and transfer it to a permanent bank (displayed on the screen) or the balloon explodes and the temporary earned money is lost	Starting capital of 100 points The probability under which box (a red one or a blue one) the token might be hidden is equal; however, the ratio of red and blue boxes varies from trial to trial and is pseudo-randomized The amount of points to win/loose (displayed on the screen) changes from trial to trial and is displayed in a sequence of five consecutive bets; participants can chose one amount to bet It is emphasized that the decision might involve conservative or risk-taking behavior	No starting capital During each trial the participants have 10 s to decide whether they want to gain / lose a fixed amount of €20 displayed on the screen or whether they want to gamble for €100; if the time limit is over the fixed amount is chosen automatically If they decide to gamble, a cube is pulled out of 24 cubes (number is at least countable); the ratio of red and blue cubes changes every trial, a red cube leads to a win of €100, a blue cube to a loss of €100; the current capital is displayed	Starting capital of €1,000 In each of the 18 trials, participants have to choose between different numbers of combinations, each associated with a different amount gain/loss: one number (€1,000), combination of two numbers (€500), of three numbers (€200), and of four numbers (€100) Gain/loss is displayed on the screen, added to or subtracted from the displayed current capital Number of round is presented on the screen

Decision-making tasks				
IGT	**BART**	**CGT**	**PAG-Task**	**GDT**
Information not (explicitly) given to the participants				
Deck A and B are the disadvantageous decks, leading to loss in the long run: high gains but also even higher losses; deck C and D are advantageous decks, leading to gain in the long run: low gains but also low losses Task consists of 100 trials	The underlying probabilities of explosion: Blue balloons have averaging explosion point at 64 pumps, the yellow balloons at 16 pumps, and the orange balloons at 4 pumps	The ratio between red vs. blue boxes varies between 9:1, 6:4, 7:3, and 8:2 Five bets were offered on each trial and represent a fixed percentage of the current capital: 5 %, 25 %, 50 %, 75 %, 95 %; depending on the condition bets were presented in a descending or ascending order Number of trials	The explicit ratio of red and blue cubes and thus the winning probability: varying according to pseudo-randomized order between 3:21, 9:15, 15:9, and 21:3 Task consists of 40 trials	One number and two number combination are associated with a winning probability less than 34 % (disadvantageous /high-risk decisions) and the three and four number combination with a winning probability of 50 % and up (advantageous/low-risk decisions); they are at least calculable
Main measures of decision-making performance				
Net score: Number of advantageous decisions minus number of disadvantageous decisions; a positive score displays good decision-making performance	To measure risk taking the *number of pumps* is counted: High number of pumps displays high risk taking	*Number of choices of the most likely outcome*, a high number displays good decision-making performance, *speed* of decision making in ms *Risk-adjustment*, the percentage of points a participant put at risk despite a high probability to lose	The *frequency of choices of the fix sum in the low winning probability;* high frequency displays good decision-making performance *Frequency of gambles in the high winning probability;* high frequency displays good decision-making performance	*Net score:* Number of advantageous/low-risk decisions minus number of disadvantageous/high-risk decisions; a positive score displays superior decision-making performance *Frequency of the riskiest choice* (one single number); a high frequency indicates disadvantageous decision making *Frequency of disadvantageous/high-risk choices* (one single number and a combination of two numbers); a high frequency indicates disadvantageous decision making

Note. IGT = Iowa Gambling Task (Bechara, et al., 1994); BART = Balloon Analogues Risk Task (Lejuez, et al., 2002), CGT = Cambridge Gamble Task (Rogers, Everitt, et al., 1999); PAG-task = Probability-Associated-Gambling Task (Bonatti et al., 2008; Zamarian, et al., 2008); GDT = Game of Dice Task (Brand, Fujiwara, et al., 2005).

For a detailed description of the decision-making tasks please be referred to the original papers mentioned above.

So far, this chapter gives a short overview about neuropsychological decision-making models and tasks used in this field of research. A detailed discussion about the assumed underlying affective and cognitive processes of decision making, the associated neural correlates of decision making, and the situational influences on it, will be presented in the following chapters (chapters 3.1 - 3.4).

3.1 Affective processes in decision making

Before going into more detail on this subject, it seems to be appropriate to describe and differentiate the terms emotion, mood, feeling, and affect, as they are often used synonymously in everyday life. Since, due to different tradition of languages these terms have differential definitions depending on the language used (Sokolowski, 2008). For example, while the term *affect* is understood as an intensive emotional state in the German language area, it is often used as synonym for the term emotion or as genus of emotion, mood, and feelings in the English language area (Ewert, 1983; E. Fox, 2008; W.-U. Meyer, Schützwohl, & Reisenzein, 2001; Sokolowski, 2008). Occasionally, affect is even used to describe the aspect of experiencing emotions (Lazarus, 1991b). In some textbooks (e.g., W.-U. Meyer, et al., 2001; Sokolowski, 2008) *emotions* are often described as time-limited, discrete reactions to internal and external incidents and they are manifested in physiological, psychological, and behavioral mechanisms. Furthermore, emotions are mostly described as object-related. In contrast, *mood* is a not object-related, affective state, which is often described to be diffuse and of less intensity but of longer duration than emotions. *Feelings* are understood as the subjective experience of emotions. However, none of these definitions is popularly accepted (W.-U. Meyer, et al., 2001) and probably differ between language areas (see above). The present thesis includes international papers which will differ in the use of the emotion terminology. In order to hinder possible content confusions, the term affect will be used in this thesis as genus of emotion, mood, and feelings as it is often done in the English language area (Ewert, 1983; E. Fox, 2008; W.-U. Meyer, et al., 2001; Sokolowski, 2008).

To dwell on the theories of emotions and the origins of emotion would go far beyond the constraints of this thesis. At this point interested parties should be referred to the works of famous theorists of emotion for example, Darwin (1872, 1965), James (1890, 1950), Schachter (1964), McDougal (1908,1960), Plutchik (1962), A. R. Damasio (1994). However, one theory associated with the affective processes underlying decision making will be discussed in details in section 3.1.2, the somatic marker hypothesis. At first, a general overview about the brain regions involved in affective processing will be given in the following sections.

3.1.1 Neural correlates of affective processing

One of the first assumptions concerning the neural correlates of affective processing was made by Cannon (1927, 1931). He postulated that the thalamus is involved in the affective response to stimuli. This was based on experiments with decorticated cats, which still showed affective reactions like intense fury, until the removal of the lower posterior portion of the thalamic region. After the removal such reactions subsided. This led the author to the assumption that the thalamus is a region which dispatches impulses that evoke an extreme degree of affective activity, although cortical government appears to be absent. However, over the years of research it became clear that there is not only one single structure involved in affective processing, but that there are rather

different networks consisting of various cortical and subcortical structures and fiber pathways (Pritzel, Brand, & Markowitsch, 2003). The limbic system (initially proposed by MacLean, 1949) is one of those networks proposed. Since then, the brain regions supposed to be involved in the MacLean's model were continuously adjusted to contemporary findings. Markowitsch (1999, 2000) described a current version of the limbic system that includes the limbic cortex, the limbic nuclei of the tel-, di-, and mesencephalon, and the fiber tracts interconnecting the structures. Here, the core of the limbic system is proposed to consist of two sub-circuits (Markowitsch, 1999, 2000): The *Papez circuit* (Papez, 1937) and the *basolateral limbic circuit* (Sarter & Markowitsch, 1985). According to Markowitsch (2000), the Papez circuit proceeds from the hippocampal formation via the fornix to the mammillary bodies. It continues via the mammilothalamic tract to the anterior thalamus. At this point the circuit proceeds either directly back to a part of the hippocampal formation (subiculum) or it goes indirectly via the cingulate gyrus into the hippocampal formation. Markowitsch (1999) described this circuit as "primarily engaged in the transfer of information from short-term to long-term memory" (p. 473). The second circuit, the basolateral limbic circuit, is assumed to be involved in the affective estimation of perceived information and decides about the valance transferred into long-term memory (Markowitsch. 2000). This circuit is suggested to be associated with brain structures such as the amygdala, the mediodorsal thalamic nucleus of the thalamus, and the basal forebrain region, as well as interconnecting fiber pathways (e.g., the ventral amygdalofugal pathway, anterior thalamic peduncle, and the bandeletta diagonalis) (Markowitsch, 1999). Rolls shared the opinion that there is a more affective and a more memory associated system (Rolls, in press). To be more precise, Rolls stated that there exists no single limbic system, but rather two limbic systems operating independently of each other. One system includes the amygdala, the anterior cingulate cortex (ACC), and the orbitofrontal cortex (OFC), and is involved in affect, reward valuation, and reward-related decision making. This is because the OFC and the amygdala are engaged in decoding and encoding of primary reinforcers (e.g., taste and touch) as well as in reward-related and punishment-related behavior (e.g., Rolls, 2000). In contrast, the second limbic system includes the hippocampus and a circuit involving the fornix, the mammillary bodies, the anterior thalamus, and the posterior cingulate gyrus, and is associated with memory (Rolls, in press). However, he further assumed that an interaction between these two systems is possible, in particular when affect provides a component of memory.

The assumption of an interaction between affective and cognitive processes in the brain has a long history. LeDoux (1989) was one of the first researches proposing interactions between cognition and affect based on the neuronal connections between the amygdala (above described as part of the affective processing systems) and the hippocampus (above described as part of the memory-associated systems) as well as the neocortex (evolutionarily recently developed cortex). Since then, many studies have occurred demonstrating the interaction between affective and cognitive processing, suggesting various brain structures to be involved depending on the context reviewed (for reviews see Dolan, 2002; Dolcos, Iordan, & Dolcos, 2011; Pessoa, 2008). Besides the studies demonstrating the involvement of the OFC and the amygdala in reward-valuation processes (e.g., Rolls, 1990, 2000), the amygdala was also found to be involved in studies investigating the relationship between perception and attention (e.g., Anderson & Phelps, 2001; M. Davis & Whalen, 2001; Dolan, 2002; Holland & Gallagher, 1999; Phelps & LeDoux, 2005). Additionally, it seems that the amygdala is also involved in implicit learning (Büchel, Morris, Dolan, & Friston, 1998; LaBar, Gatenby, Gore, LeDoux, & Phelps, 1998) as well as encoding and recall of affective stimuli (Cahill et al., 1996; Canli, Zhao, Brewer,

Gabrieli, & Cahill, 2000). Some studies, assumed that the amygdala works automatically (Dolan, 2002; Öhman, 2002) and independent of awareness, while others demonstrated that the amygdala functions are tied to top-down processes (Ishai, Pessoa, Bikle, & Ungerleider, 2004; Pessoa, McKenna, Gutierrez, & Ungerleider, 2002). However, Dolcos and colleagues demonstrated that in addition to the amygdala also the medial temporal lobe was activated during encoding of affective stimuli (Dolcos, LaBar, & Cabeza, 2004) and recall of affective long-term memory information (Dolcos, LaBar, & Cabeza, 2005). Other studies have shown that the recall of affective states associated with past affective experiences engages the upper brainstem nuclei, the hypothalamus, the insular cortex, the somatosensory cortex, and the OFC (A. R. Damasio et al., 2000). More recently, the ACC was postulated to be involved in regulation of affect (Bush, Luu, & Posner, 2000; Davidson et al., 2002), and conscious affective experience (Lane et al., 1998).

In his review Pessoa (2008) gave a comprehensive overview about the brain regions involved in affective processing (see Figure 3 and Figure 4). Based on an informal assessment of the frequency with which they appeared in the literature, he distinguished between core and extended regions: The core regions are those which were reported more frequently in the literature: They involve subcortical (see Figure 3) the amygdala, the nucleus accumbens (part of the basal ganglia), and the hypothalamus.

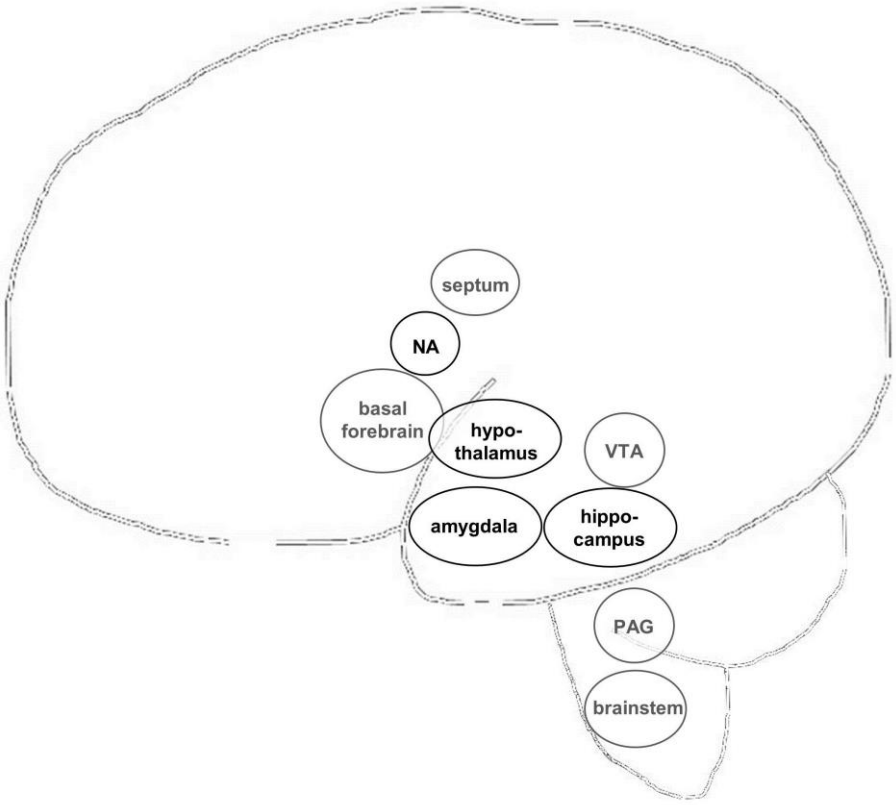

Figure 3 The subcortically brain regions involved in affective processing modified from Pessoa (2008).

The core regions involved in affective processes are highlighted in black, while the extended regions are displayed in grey color. NA = nucleus accumbens; VTA = ventral tegmental area; PAG = periaqueductal grey.

The cortical core regions (see Figure 4) are the OFC, the ACC (especially the rostral part), and the ventromedial prefrontal cortex (vmPFC). Extended regions were reported less frequently and include

subcortically (see Figure 3) the brainstem, the ventral tegmental area, the hippocampus, the periaqueductal grey, the septum, and the basal forebrain. Cortically (see Figure 4), they include the anterior insular cortex, the prefrontal cortex (PFC), the anterior temporal lobe, the posterior cingulate cortex, the superior temporal sulcus, and the somatosensory cortex.

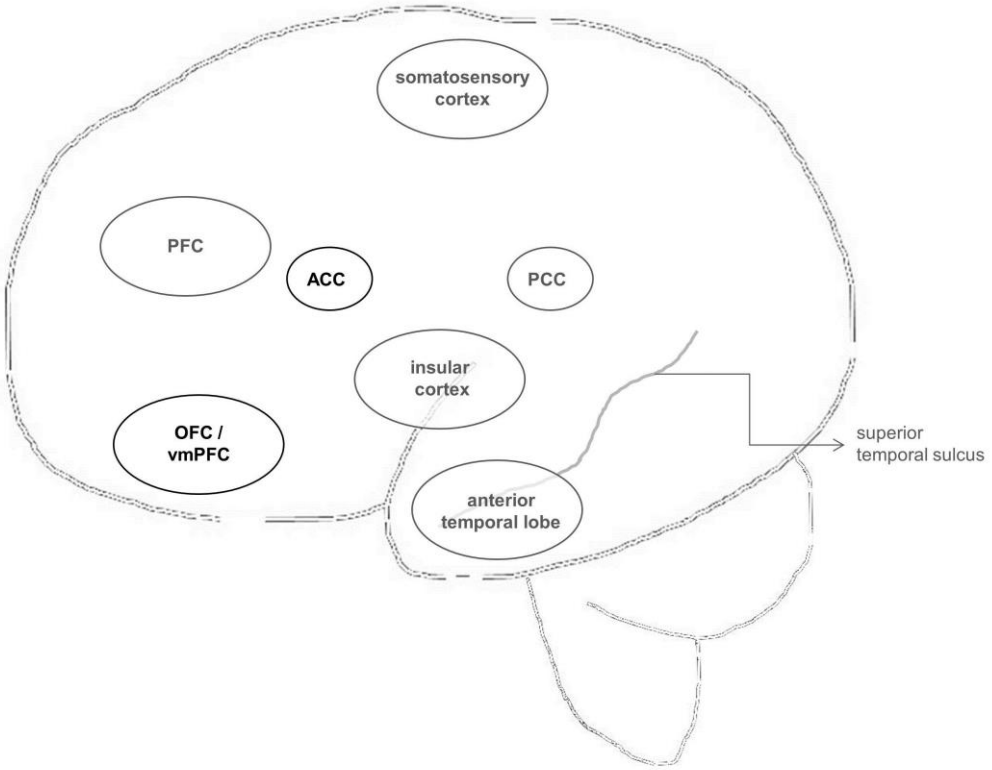

Figure 4 The cortically brain regions involved in affective processing adapted from Pessoa (2008).

The core regions involved in affective processes are highlighted in black, while the extended regions are displayed in grey color. PFC = prefrontal cortex; ACC = anterior cingulate cortex; OFC = orbitofrontal cortex; vmPFC = ventromedial prefrontal cortex; PCC = posterior cingulate cortex.

Moreover, Pessoa (2008) argued that especially the lateral PFC seems to be a region for the integration of cognition and affect. With regard to this assumption he referred to studies in which the dorsolateral prefrontal cortex (dlPFC) and the lateral PFC showed changes in neural activity only when participants had to do cognitive and affective processing simultaneously. For example, in the study by Perlstein, Elbert and Stenger (2002) participants were asked to maintain in mind neutral and affective stimuli. The authors were interested whether the maintenance-related activity in the PFC was influenced by the affective tone of the stimuli. Using *functional magnetic resonance imaging* (fMRI; see section 4.3.4 for detailed information about this technique) they found that the maintenance-related activity in the dlPFC especially was modulated by the valance of the stimuli: Compared with neutral stimuli, pleasant stimuli increased the activity while unpleasant stimuli decreased it. Interestingly, when participants had only to detect the stimuli without maintaining the information in mind the dlPFC was not affected. This indicates that the modulation of the activity in the dlPFC by the affective valence was particular to the experimental context of the maintenance task. Similar, in a second fMRI study participants had to watch short video clips with differential affective content after which they performed a working memory task (Gray, Braver, & Raichle, 2002). The authors demonstrated a bilateral activity in the lateral prefrontal

cortex associated with the affective and working memory tasks components. This activation pattern could not be predicted by information either of the affective or working memory task in isolation. Therefore, they assumed that this activation reflects both components equally. Furthermore, a recent study revealed that the performance of a cognitive task (2-back with neutral words) was accompanied by increased activation in cognitive-related brain areas and a decrease of activity in affect-related areas (Grimm, Weigand, Kazzer, Jacobs, & Bajbouj, 2012). In contrast, processing of affective words (independent of valence) in the 2-back task increased the activation of cognitive-related regions. This supports the assumption that lateral prefrontal areas appear to be a platform for affective and cognitive interaction.

Overall, those studies demonstrate that many different brain regions are involved in affective processing, which are also involved in cognitive processing, leading to an interaction between affect and cognition (Dolan, 2002; Dolcos, et al., 2011; Pessoa, 2008; Rolls, in press). In this context it is not surprising that affective processes are involved in decision making, as postulated by Rolls (for an overview see Rolls, 2014; Rolls, in press). At this point one theory has to be mentioned, which had a tremendous influence on the neuropsychological decision-making research: the *somatic marker hypothesis* (A. R. Damasio, 1994). In comparison to Rolls who especially highlighted the reward-valuing processes in decision making associated with the OFC, A. R. Damasio concentrated on the somatic states/ gut feelings (somatic markers see section 3.1.2) which modulate human decision making. The next section will discuss the somatic marker hypothesis in more detail.

3.1.2 Underlying affective processes in decision making: The somatic marker hypothesis

In both decision-making models (see Figure 1 and Figure 2) the underlying affective processes are postulated to be associated with somatic markers. The *somatic marker hypothesis* describes those processes as somatic (i.e., bodily) and able to regulate decision-making behavior (Bechara & Damasio, 2005; A. R. Damasio, 1994; A. R. Damasio, et al., 1996; A. R. Damasio, Tranel, & Damasio, 1991). The hypothesis is based on various remarkable observations in neurological patients with local lesions in the frontal brain (A. R. Damasio, et al., 1996). One of those patients was Phineas Gage who suffered from frontal brain lesions due to an accident at work (Harlow, 1848, 1868): He was a blasting foreman at the American railroad construction company. On the day of his accident the blast started premature and the iron rod (with that he tamped the blasting powder with sand into the whole of the rock which was to blast) entered Gages head through his left maxillary bone and passed completely through the frontal brain to exit afterward with high speed through the cranium (c.f. Bigelow, 1850; A. R. Damasio, 1994; Harlow, 1848). Even though Phineas survived this accident, he suffered from a loss of vision of his left eye. Moreover, as time went by his whole personality changed: While he was described as a smart business man with a well-balanced mind before the accident, henceforth he was capricious and disrespectful. Furthermore, it appeared that from now on Phineas often had fits of temper and often changed his mind regarding his plans for the future (c.f. A. R. Damasio, 1994; Macmillan, 2000). However, his change did not include motoric, language, and cognitive functions such as intelligence, memory, and new learning (H. Damasio, Grabowski, Frank, Galaburda, & Damasio, 1994). Five years after Phineas' death, 1861, Harlow got the family's approval to exhume the skull. Since then the skull and the iron rod, which was buried with Phineas Gage, are exhibited in the Warren Anatomical Medical museum at Harvard University (A. R. Damasio, 1994). Although Harlow (1868) had already assumed that the personality changes were associated with the focal

damage in the frontal region, and Ferrier (1878) postulated that those lesions do not involve brain areas associated with motor and language functions, only 1994 these assumptions could be supported. In this year H. Damasio and colleagues were able to create a three-dimensional reconstruction of Phineas' skull and simulate the trajectory of the iron rod, using a new neuroimaging technique named Brainvox (H. Damasio & Frank, 1992). They could prove that neither the supplementary motor area nor Broca's area suffered from lesions. However, the authors found that especially the ventral and medial part of the prefrontal cortex (PFC) was damaged. H. Damasio and colleagues (1994) argued that these lesions were the reason why Phineas was not able to plan his future, to stick to social rules which he once learned, and to choose course of actions which would be advantageous for his own good.

A second prominent case was patient EVR who demonstrated antisocial traits after an ablation of a tumor in bilateral orbital and lower mesial frontal cortices (Eslinger & Damasio, 1985). After this surgery EVR also demonstrated a change in personality: from an esteemed member of a business community to a man who made only sort-sighted business and financial decisions. Despite his average to outstanding cognitive functions he made risky and disadvantageous decisions again and again. Moreover, the assumption that he had lost his knowledge and ability to behave correctly in social situations could not be supported (Saver & Damasio, 1991). Instead, it was recognized that EVR and patients with lesions in the vmPFC and the OFC in general have problems with the anticipation of the consequences of their actions and in recognizing and describing their affects (Eslinger & Damasio, 1985; Stuss, Gow, & Hetherington, 1992).

Due to the fact that those patients showed unimpaired cognitive ability A. R. Damasio (1994) assumed that rational thinking is obviously not sufficient enough to make a decision. Furthermore, he argued that in a social decision-making situation too many information are given and too many outcomes are possible as that a person may be able of capturing them all before a decision is made. It would take a long time until a person finally decides. This is rarely the case in social decision-making situations. Therefore, A. R. Damasio (1994) postulated that in order to make a decision in such situations, affect has an important role. He supposed that before a person has made a cost-benefit analysis he/she has a gut feeling when thinking about the possible outcomes and alternatives to react. Moreover, he assumed that it is this gut feeling that guides the decision into a certain direction. Due to the fact that those gut feelings affect the body and mark certain mental representations he named them somatic markers. These markers may act as an alarm signal when a negative outcome is associated with a certain alternative and may lead to a refusal of this alternative and to a choice of another one. However, they may also act as a start signal in case the alternative is associated with a positive outcome. On a neural level it was suggested that especially the vmPFC is involved. The vmPFC has various afferent pathways to sensory and bioregulatory brain regions for example, the amygdala, the hypothalamus, the cingulate gyrus, the nuclei of the brainstem, and the basal forebrain. Through this connection it is possible that information of a given situation and the affect recently experienced in this kind situations are linked and may be modified and reactivated in similar situations (A. R. Damasio, 1989a, 1989b). Overall, A. R. Damasio described two alternative routes of how the reactivation of the somatic markers may proceed (Bechara & Damasio, 2005; A. R. Damasio, 1994): the *body-loop* and the *as-if-body-loop*. Within the body-loop the vmPFC and the amygdala initiate the body through the brainstem nuclei to adopt a certain somatic state. In turn the somatic state is then processed by the insular cortex and the somatosensory cortex. Within the as-if-body-loop the body is left out and the vmPFC along with the amygdala activate the somatosensory and the insula cortex directly. Both cortices

work as if they have received the signals from the body. Even though this pattern of activity is not the same as the one produced by the body, it is still able to influence the decision-making process. The enacted somatic state (independent of the loop by which it was activated) then acts consciously or unconsciously. Moreover, it is postulated that somatic markers reinforce the activation of attention and working memory processes, which are associated with the dlPFC (see also section 3.2.1) and other high order association cortices (Bechara & Damasio, 2005). This again enables the preselection of information, so that in a complex and uncertain decision-making situation only profitable alternatives are represented in the brain. (For a more detailed description of the somatic marker hypothesis and the associated neural processes, please see Bechara & Damasio, 2005; Bechara, Damasio, Damasio, & Lee, 1999; A. R. Damasio, 1994; A. R. Damasio, et al., 1996; A. R. Damasio, et al., 1991; Dunn, Dalgleish, & Lawrence, 2006; Naqvi, Shiv, & Bechara, 2006; Schiebener, Staschkiewicz, & Brand, 2013).

A. R. Damasio concluded that in certain situations healthy subjects i.e., without neurological and psychiatric illness, are able to recall composite memories formed by facts and somatic body states that were evoked in the individuals' experience with the facts (A. R. Damasio, et al., 1996). While the facts need to be held permanently in a dispositional form in the association cortices, somatic states can be retrieved on demand and do not need to be stored. Regarding the patients with lesions in the vmPFC for example, Phineas Gage and EVR, A. R. Damasio assumed that while they are able to retrieve the facts, they fail to evoke the somatic states accompanied with those facts (A. R. Damasio, et al., 1996). This again may lead to odd behavior in situations where people need to rely on somatic states, for example, social situations and decisions under ambiguity which might explain the non-social behavior of Gage and EVR. Studies investigating the affective response of patients with lesions to the vmPFC supported the assumptions (A. R. Damasio, Tranel, & Damasio, 1990; A. R. Damasio, et al., 1991; Tranel, Damasio, & Damasio, 1995). A. R. Damasio and colleagues (1991) demonstrated affective and neutral pictures to patients with lesions to the vmPFC, to patients with lesions outside the PFC, and to a control group with healthy participants. In order to measure a potential change in the somatic state (affective response) the authors used the *skin conductance response* (SCR). The SCR measures temporary changes in the electrical conductance of the skin in relation to specific stimuli and thoughts (Pinel, 2001). Therefore, electrodes are placed at the hands of the participants to derive the electrodermal activity (for detailed information about SCR refer to Boucsein, 1992; Bouscein, 1988). The results of the study by A. R. Damasio and colleagues (1990, 1991) are straightforward: While the two groups without lesions to the vmPFC showed standard SCRs to the affective pictures and little or no response to the neutral stimuli, the patient group with lesions to the vmPFC did not show any reaction to the affective stimuli, too. Although, all three groups demonstrated normal SCRs to startling stimuli such as loud noise or deep breath, which indicates that the patients with damage to the vmPFC are able to evolve SCRs, they did not show these reactions to stimuli with affective components. Further on, Trane and colleagues (1995) demonstrated that lesions to the vmPFC enable patients to retrieve facts (e.g., this is a familiar face), but that this lesions impair SCR discrimination. Those findings led the authors to the suggestion that the missing development of somatic markers may be the reason why patients with lesions to the vmPFC are unable to make advantageous decisions in uncertain situations. Overall, the findings show that somatic markers seem to be an inherent part of the decision process and influence the decision as covert biases, which is in line with the decision-making model of Bechara and colleagues (1997).

Studies investigating the potential role of somatic markers as part of the underlying affective processes are summarized in the following section.

3.1.2.1 The role of affective processes in decision making under ambiguity

In order to operationalize personal, ambiguous, real-life decision making in the laboratory and thus, to have the opportunity to test the assumption of the somatic marker hypothesis, the IGT was developed (Bechara, et al., 1994; for a brief description of the IGT see also Table 1). Nowadays, the IGT is mostly used in its computerized version (c.f. Bechara et al., 2001; Bechara, Tranel, & Damasio, 2000). The first study using the IGT revealed that patients with lesions in the vmPFC chose the disadvantageous card decks more often than participants with no brain lesions (Bechara, et al., 1994). In order to test whether this may be due to missing somatic markers, in another study the SCRs were additionally measured during the IGT performance (Bechara, Tranel, Damasio, & Damasio, 1996). Results demonstrated that control participants with no lesions to the brain and no psychiatric or neurological disorders as well as patients with lesions to the vmPFC developed SCRs after they received a gain or a loss. During the course of the game the control participants also developed SCRs before they made a choice, i.e., anticipatory SCRs. In particular, the SCRs were higher before a disadvantageous decision than before an advantageous decision. In contrast, the patients did not develop anticipatory SCRs. On a behavioral level, the control group demonstrated additionally better IGT performance than the patient group. This led the authors to the assumption that the missing SCRs may be a correlate of their insensitivity to future outcomes (for more detailed information see also Bechara, Tranel, et al., 2000), which again supports the suggestion that somatic markers biases the decision-making process by marking a decision option as positive or negative (also found in following studies: Suzuki, Hirota, Takasawa, & Shigemasu, 2003; Wagar & Dixon, 2006). Further support for the somatic marker hypothesis comes from a subsequent study (Bechara, et al., 1997): In this study, control participants and patients with lesions to the vmPFC were asked every 10 cards (starting at card 20, where participants had already made some experiences with the IGT) whether or not they already know what is going on in the task and how they feel about the task. Additional SCRs were measured. The authors found that control participants started to make advantageous decisions before they had any conscious knowledge about the task (second block of the IGT, i.e., card 20-40, called pre-hunch phase). Moreover, control participants generated anticipatory SCRs whenever they thought about making a risky choice, even though they did not had any explicit information about what constitutes a risky decision. In contrast, patients did not develop anticipatory SCRs at all and even though they knew which strategy was the best, they still decided disadvantageously until the end of the game. Bechara and colleagues (1997) concluded that in healthy participants, the unconscious biases/somatic markers (anticipatory SCRs) precede the conscious knowledge and guide the decision-making behavior. Furthermore, the subsequent reasoning/working memory process (in which the knowledge is retrieved and processed, see the decision-making model under ambiguity in Figure 1) may be facilitated by those biases/somatic markers. A study of the year 1999, additionally demonstrated that besides the vmPFC also the amygdala appears to be involved in the somatic states (Bechara, et al., 1999). Patients with lesions to the amygdala were not able to develop SCRs as a response to feedback given in the decision-making task. Likewise, they demonstrated impaired decision-making performance. Due to the fact that patients with lesions in the vmPFC developed feedback SCRs, but also demonstrated impaired decision-making performance the authors concluded that both areas are differently involved in the development of somatic markers. Bechara

and colleagues (1999) assumed that while the amygdala attaches affective attributes to stimuli, the vmPFC processes the information coming from the amygdala. Thus, lesions to either one of these structures lead to an impairment of somatic markers and therefore to decreased decision-making performance.

Other studies investigating decision-making performance in different patient groups support the assumption of impaired affective processing due to missing SCRs, which leads to disadvantageous decision making, for example, in substance dependent individuals (Bechara & Damasio, 2002), in patients suffering from Urbach-Whiete disease (Brand, Grabenhorst, Starcke, Vandekerckhove, & Markowitsch, 2007), Huntington's disease (Campbell, Stout, & Finn, 2004), multiple sclerosis (Kleeberg et al., 2004), obsessive compulsive disorder (Starcke, Tuschen-Caffier, Markowitsch, & Brand, 2009), and anorexia nervosa (Tchanturia et al., 2007). Furthermore, studies investigating patients with anxiety disorder (Maner et al., 2007; Miu, Heilman, & Houser, 2008), major depression disorder (Must et al., 2006; Smoski et al., 2008), or narcolepsy with cataplexy (Bayard et al., 2011; Delazer et al., 2011) demonstrated that the patients' decision-making behavior appears to be associated with altered affective processes. Overall, the studies present two different approaches trying to explain these affective alterations. Some authors argued that it is an altered modulation of somatic signals (somatic markers), which is associated with the patients' decision-making performance: Miu and colleagues (2008) assumed that such an alteration (in their study: increased anticipatory SCRs before advantageous instead of disadvantageous decisions) is associated with impaired decision-making performance. Maner et al. (2007) and Smoski et al. (2008) found risk-avoidant decision-making behavior in their patient groups, which might reflect an alteration of somatic signals (in this case: a faster or stronger acquisition of somatic markers in response to negative feedback; c.f. Smoski, et al., 2008). In contrast, other authors discussed altered reward processing to be associated with the patients' decision-making performance (Bayard, Abril, et al., 2011; Delazer, et al., 2011; Must, et al., 2006): That means that these patients seem to be hypersensitive to reward and therefore, choose alternatives with high immediate reward/gain more often than control participants, regardless of the even larger punishment/loss in the future. It is argued that such a hypersensitivity of reward might be due to a general blunting of affective reactivity: To compensate their reduced reactivity to affective stimuli, the patients choose higher immediate affective valence, irrespective of the amount of future punishment or reward (Bayard, Abril, et al., 2011; Must, et al., 2006). Even though there are no consistent findings regarding the decision-making performance in certain patient groups [anxiety disorder: impaired (Miu, et al., 2008) vs. non-impaired (Maner, et al., 2007); major depression disorder: impaired (Must, et al., 2006) vs. non-impaired (Smoski, et al., 2008)], all studies suggest affective processing to be involved in decision making under ambiguity. Thus, these studies are in line with the decision-making model of ambiguity (see Figure 1) and the somatic marker hypothesis (see section 3.1.2).

Overall, these studies support the assumption of affective processes in decision making under ambiguity, which appear to be associated with unconscious somatic reactions (e.g., SCRs). However, there were repeatedly studies questioning the extent of their involvement and supplying different explanatory approaches for the deficits in the IGT (for reviews see Buelow & Suhr, 2009; Dunn, et al., 2006). For example, in their review Dunn and colleagues (2006) criticized that the psychophysiological findings connecting the generation of somatic markers with successful decision-making performance is only of correlative nature. Therefore, it cannot be said whether the anticipatory SCRs developed in the decision-making process are the end product of a decision or whether they are involved in the development of a decision as a key feature. Attempts to yield causal

evidence by investigating for example, patients with impairments to the vagus nerve or the spinal cord led to contradictory findings. The assumption was that those patients who are not able to get feedback of the somatic states due to the impairments, should demonstrate decreased decision-making performance. However, while one study could only demonstrate trends in the assumed direction (C. O. Martin, Denburg, Tranel, Granner, & Bechara, 2004), a second study did not find deficits in IGT performance (North & O'Carroll, 2001). North and O'Carroll suggested that the good decision-making performance may be due to the fact that patients with lesions to the vagus nerve or the spinal cord have adapted to the loss of peripheral feedback (body loop) and compensate it by the extensive use of the as-if-loop. Dunn and colleagues (2006) argued that it seems to be impossible to create a scenario in which the body loop is disturbed and the as-if loop cannot be used, making it difficult to test the causality of the somatic markers. Other authors assumed that the deficit in IGT performance in patients with lesions in the vmPFC may rather be due to impaired reversal-learning than due to impaired development of somatic markers (Fellows & Farah, 2005). Fellow and Farah (2003) demonstrated that patients with lesions to the vmPFC had problems in changing their choices from a previous positive card deck that emerged to a disadvantageous deck, to a previous negative card deck that now is rather advantageous. Moreover, patients with lesions to the vmPFC performed as well as healthy control participants when the contingencies of the IGT were changed, so that the disadvantageous deck does not lead to an initial gain. Overall, it is often mentioned critically that there may be an underestimation of cognitive processes in the decision-making process in ambiguous decisions (Dunn, et al., 2006; Maia & McClelland, 2004). However, regarding the model of Bechara and colleagues (1997) cognitive processes are postulated to be involved. Studies investigating such an involvement are discussed in chapter 3.2.2.1.

At this point it should be summarized, that the given data adumbrate a clear pattern of the involvement of affective processes in decision making under ambiguity. Although, the involvement of somatic markers in decision making under ambiguity still appears to be unclear and leaves space for other explanations. The next section will discuss their involvement in decision making under risk.

3.1.2.2 The role of affective processes in decision making under risk

Affective processes associated with somatic markers are postulated to be involved in decision making under risk, too (c.f. Brand et al.'s decision-making model in Figure 2). Studies investigating the underlying affective processes in decision making under risk mostly used the GDT (for a brief description of this task see Table 1. Only one study, analyzing affective processing in terms of feedback processing, used the BART (Euser, Meel, Snelleman, & Franken, 2011; for a brief description of the BART see Table 1) and will also be shortly presented. However, the involvement of brain regions associated with affective processing (e.g., the vmPFC/OFC) was also found for the CGT (Clark et al., 2008) and the PAG-task (Bonatti, et al., 2008) as will be addressed in detail in section 3.3 (for a brief description of the CGT and PAG-task see Table 1). In the current section, only studies are summarized which explicitly examined underlying affective processes of decision making under risk.

Studies scrutinizing the potential role of somatic markers (in terms of SCRs) in decision making under risk using the GDT revealed heterogeneous findings. Brand, Grabenhorst, and colleagues (2007) found diminished decision-making performance in patients suffering from Urbach-Wiethe disease (associated with impairments of the amygdala) in comparison with a healthy control group, i.e., participants without psychiatric

or neurological impairments. Moreover, the authors showed that SCRs were reduced in the patient group compared with the control group, especially before (anticipatory SCRs) and after (feedback SCRs) a high-risk decision was made. Within the control group SCRs were higher before and after a high-risk decision than before and after a low-risk decision (Brand, Grabenhorst, et al., 2007). However, after correction for multiple comparisons the differences for anticipatory SCRs failed to reach significance, indicating a clearer pattern for feedback SCRs (differences survived the correction for multiple comparisons) than for anticipatory SCRs in the GDT. This appears to be in contrast to the IGT, in which the feedback and the anticipatory SCRs indicated a similar pattern: Higher SCRs before and after disadvantageous decisions than before and after advantageous decisions (even after correction for multiple comparisons). Brand, Grabenhorst, and colleagues (2007) argued that this displays the different role of feedback in each task: In the IGT the use of feedback appears to be especially involved in finding out how to make an upcoming advantageous decision. In contrast, in the GDT the feedback seems rather to be used, in order to evaluate whether the current strategy of decision making is advantageous than to influence an upcoming decision. Varied feedback SCRs were also found in two other studies measuring SCRs during GDT performance (Euteneuer et al., 2009; Starcke, et al., 2009). Euteneuer and colleagues (2009) found reduced SCRs after losses, but not after gains in Parkinson patients as compared with healthy control participants. Additionally, the patient group chose disadvantageous/high-risk decisions more often than the control group. In contrast, patients suffering from compulsive disorder did not show diminished decision-making performance (Starcke, et al., 2009). However, SCR analyses across both groups (patients suffering from obsessive-compulsive disorder and healthy control participants) demonstrated a comparable pattern to that found in control participants in the study by Brand, Grabenhorst, and colleagues (2007): Higher feedback SCRs after high-risk decisions than after low-risk decisions. Comparable findings were found in a study using the BART and an *electroencephalogram* (EEG) to measure *event-related brain potentials* (ERPs) associated with feedback processing in decision making under risk (Euser, et al., 2011). The authors were interested whether or not alcohol affects the neural mechanisms of feedback processing and outcome evaluation during risky decision making. Therefore, one group received a moderate dose of alcohol (0.65g/kg alcohol) while the other group received a non-alcoholic placebo beverage. Euser and colleagues (2011) assumed that drunken participants revealed a hyposensitivity to negative feedback with reduced ERPs leading to risky decision making. In order to measure the ERPs, electrodes were placed at the fronto-central region of the participants' head during the performance of the BART. Results revealed that alcohol consumption does not impair the ability of feedback evaluation but the integration of feedback, in particular negative feedback (i.e., loss). This was indicated by a reduction of feedback-related amplitude (P300). This amplitude (P300) is associated with later, more elaborated appraisal of outcome evaluation. In contrast, the *feedback-related negativity* reflects an early, rapid evaluation of the affective outcome and is associated with larger amplitudes after negative feedback than for positive feedback (c.f. Euser, et al., 2011). This finding is in line with the assumption of Brand, Grabenhorst, and colleagues (2007) that in decision making under risk feedback processing may be more essential in the evaluation process. Overall, the represented studies demonstrate the involvement of SCRs or ERPs (both associated with feedback processing) in decision making under risk which is associated with somatic markers. However, the engagement of the somatic markers seems to be at another moment in the decision-making process than in decisions under ambiguity: They may be more involved in feedback evaluation processes than in anticipated processes of an upcoming decision.

Further studies investigated the involvement of affective processes in decisions under risk in different patient groups each associated with impairments to frontal brain regions (e.g., the vmPFC). At the first glance, the findings appear to be inconsistent: The first group of studies found relationships between affective processing in terms of impairments in utilization of (affective) feedback and diminished decision-making performance, for example, in patients suffering from pathological gambling (Brand, Kalbe, et al., 2005; Labudda, Wolf, Markowitsch, & Brand, 2007), Korsakoff's syndrome (Brand, Fujiwara, et al., 2005; Brand et al., 2009), borderline personality disorder (Svaldi, Philipsen, & Matthies, 2012) and Parkinson's disease (Brand et al., 2004). In contrast, the second group of studies did not find such impairments, for example, in patients suffering from obsessive-compulsive disorder (Starcke, et al., 2009), bulimia (Van den Eynde et al., 2011), temporal lobe epilepsy (Labudda et al., 2009), and schizophrenia (Fond et al., 2012). However, the difference between those two groups of studies is the fact that patients of the first group, who demonstrated impaired utilization of the feedback, additionally demonstrated impaired cognitive functions. On the contrary, the patients of the second group of studies performed all well on cognitive tests. Those findings in combination with the findings concerning feedback processing suggest that deficits in feedback processing may be compensated by cognitive processing, explaining the inconsistent pattern of findings mentioned above. To some extent such cognitive compensation was also found in a subgroup analysis in the study by Brand and colleagues (2004): On a descriptive level the analysis revealed that patients with cognitive dysfunctions (i.e., executive dysfunctions; for more information about executive functions see chapters 3.2) but unimpaired feedback processing, choose the disadvantageous decisions more often than patients with disturbed feedback processing but unimpaired cognitive functions. However, those who had impairments in both, cognitive functions and feedback processing, showed the worst decision-making performance. This suggests that cognitive dysfunctions seem to lead to more inferior decision-making performance than disturbed feedback processing, but that an impairment of both is even worse. In line with this assumption are further findings of the research group of Brand and colleagues (Brand, 2008; Brand, Laier, et al., 2009): They investigated the influence of a disrupted (affective) feedback route on decision making under risk. Therefore, the research group invented a modified version of the GDT, in which the feedback is withheld and compared the performance in this task with the decision-making performance in the original version of the GDT. While the first study (Brand, 2008) demonstrated that decision-making performance is diminished when the (affective) feedback route is disturbed (i.e., missing feedback in the GDT), the second study (Brand, Laier, et al., 2009) revealed that cognitive functions such as cognitive intelligence and strategy application moderate this effect: Participants with superior cognitive functions performed the GDT without feedback as well as participants who received feedback in the GDT, while participants with less superior cognitive functions displayed impaired decision making. A recent study aimed to investigate the underlying processes of GDT performance (Schiebener, Zamarian, Delazer, & Brand, 2011) and to give further information about the constitution of the (affective) feedback route in decision making under risk. Among other results, which are discussed in section 3.2.2.2, Schiebener and colleagues (2011) found in their second experiment that implicit learning from feedback, measured by the first 40 trials in the IGT, seemed to be involved in GDT performance. However, it explained less variance of the GDT performance than executive functions did (for more information of executive functions and their role in decision making see section 3.2 and 3.2.2.2) in their first experiment. The authors pointed out that this is another hint in the direction that (affective) feedback processing in the GDT appears to have an executive component; probably because it is used to

evaluate whether the current decision behavior or strategy is efficient or not as was assumed by Brand, Grabenhorst, and colleagues (2007) before (see also the discussion in Brand, Heinze, Labudda, & Markowitsch, 2008). However, for individuals with impaired cognitive abilities, to whom the contingencies of the task are not that clear, the feedback is essential to learn the rules (Brand, 2008; Brand, Laier, et al., 2009).

Overall, the results of the studies emphasize that affective processing is also involved in decision making under risk. In contrast to decision making under ambiguity, in which the affective processes in terms of somatic markers are essential for anticipatory processes of a decision, in decision making under risk somatic markers seem to be more involved in evaluative feedback processes. That means, in decisions under ambiguity somatic markers are involved in the guidance of a decision. In contrast, in decisions under risk they are involved in for example, the evaluation of a certain decision strategy whether it leads to advantageous decisions or not (for more information about decision strategies see Brand, Heinze, et al., 2008). So far, it was already pointed out repeatedly that cognitive processes are involved in decision making under risk but also under ambiguity and appear to interact with affective processes. Hence, the next section will go into detail on underlying cognitive processes in decision making, in particular on executive functions.

3.2 Cognitive processes in decision making with a focus on executive functions and working memory

The decision making models of ambiguity and risk postulate the involvement of several cognitive processes such as working memory, executive functions, reasoning, and the application of decision strategies (see section 3, Figure 1 and Figure 2). Due to the fact that the majority of studies examined the role of working memory and executive functions in decision making under ambiguity and risk, the following sections will focus on these functions in particular.

Working memory is described as a platform where information is maintained and/or manipulated (e.g., Baddeley, 2003; Baddeley & Della Sala, 1996). It provides an important link between perception and controlled action (Baddeley, 1998b). In contrast, the "concept of executive functions still awaits a formal definition" (Jurado & Rosselli, 2007, p. 213). On one hand there is a collective understanding that executive functions adapt humans action and cognition to changing situations in order to demonstrate goal-directed behavior (e.g., Alvarez & Emory, 2006; Chan, Shum, Toulopoulou, & Chen, 2008; Collette et al., 2005; Hobson & Leeds, 2001; Jurado & Rosselli, 2007; Lezak, Howieson, & Loring, 2004; Miyake & Friedman, 2012). On the other hand, there is still a debate on the exact definition of executive functions (Eslinger, Lyon, & Krasnegor, 1996; Stuss & Alexander, 2000). Moreover, it is still unclear whether they are organized as one united executive function or as diverse executive functions: Some researchers assumed a unitary approach (Barkley, 1997; Pennington, Bennetto, McAleer, & Roberts, 1996) with inhibition and working memory as underlying mechanism, while others suggested a non-unitary approach with various distinguishable executive functions (e.g., Alvarez & Emory, 2006; Jurado & Rosselli, 2007; Lehto, 1996; Salthouse, Atkinson, & Berish, 2003; Stuss & Alexander, 2000). A combination of both is suggested by Miyake and colleagues (2000). They assumed that there are clearly distinguishable executive functions that share some underlying commonality.

In order, to get a better understanding of executive functions and the connection with working memory, the following four popular approaches or rather conceptions of executive functions will be summarized.

Thereafter, the potential role of executive functions and working memory in decision making under ambiguity and risk will be discussed (see section 3.2.2.1 and 3.2.2.2).

The *supervisory attentional system (SAS) model* by Norman and Shallice (Norman & Shallice, 1986; Shallice & Burgess, 1991a, 1991b) postulates two systems that are responsible for different processes. It is suggested that the *contention scheduling* (CS) system is involved in demanding but routine actions (e.g., dropping of the kid at the kindergarten before driving to work). It is assumed that situational influences trigger more than one schedule of action and that the CS-system is responsible for the selection of one proper schedule that is activated automatically (e.g., at first driving to the kindergarten, dropping of the kid and afterward, driving to the office and start working). In contrast, the SAS is suggested to be involved in non-routinized situations (e.g., the kid is ill). In this kind of situations, it is assumed that this system evaluates the current schedule and adapts it to the changed circumstances (e.g., the parent need to reschedule the daily plan, by driving to the doctor and cancel work or find a babysitter). In subsequent versions of the SAS-model the generation and selection of strategies as well as the evaluation and monitoring of actions are described as the important processes of the SAS (Burgess & Shallice, 1996; c.f. Drechsler, 2007; Shallice, 2002).

A second model often described in the literature of executive functions is the *working memory model*, first suggested by Baddeley and Hitch (1974). In this model, working memory is understood as a limited capacity system, temporarily maintaining, and storing information. It is assumed that it moreover allows the manipulation of stored information by providing a link between perception, long term memory, and action (Baddeley, 1998b, 2003; Baddeley & Della Sala, 1996). Furthermore, it is suggested that it facilitates complex tasks such as reasoning, comprehension, and learning (Baddeley, 2003, 2010). The advanced version of the working memory model (see Figure 5), the *multicomponent model*, comprises four specific functional components and was advanced in order to specify the proposed control mechanisms (SAS-system) by Norman and Shallice (1986). The first component is the *phonological loop* that is assumed to enable language acquisition in two ways: First, the phonological store holds representations of phoneme sequences for a few seconds before they fade. Second, the articulatory system facilitates learning by rehearsal and thereby refreshing the phoneme sequences in the store (Baddeley, 2003, 2010). The second component the *visuo-spatial sketchpad* is suggested to be important in evolving semantic knowledge about the appearance and utilization of objects. However, it is limited in capacity to about three or four objects. Moreover,, it is postulated that it is crucial for spatial orientation and geographical knowledge (Baddeley, 2003, 2010). The third functional component is the *central executive* that is assumed to be an attentional control instance. Hereby, it is backed up by the other two sub-systems, which are therefore also called slave systems (Baddeley, 1998b). The later added *episodic buffer* (fourth component) is seen as a temporary store of the central executive, which has a limited capacity. It is suggested to be multi-dimensional coded and therefore can integrate different systems (e.g., phonological loop, visuo-spatial sketchpad and long-term memory), and combine the information (Baddeley, 2003, 2010). In this model the central executive is assumed as one system, but Baddeley and colleagues suggested that it may contain various subcomponents (Baddeley, 1996, 2003; Baddeley & Logie, 1999): the coordination of more than one task, switching between strategies, selective attention to one stimuli, inhibition of the irrelevant ones, and holding and manipulating information in long-term memory (Baddeley, 1996). Studies demonstrating dissociation in performance among various executive tasks are in line with this assumption (e.g., Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999).

Moreover, Miyake and colleagues demonstrated that the intercorrelations among different executive tasks of different studies are low (r = .40 or less) and often not statistically significant (see Miyake, et al., 2000, p. 52). This is a further support for the assumption that executive functions may be fractionated.

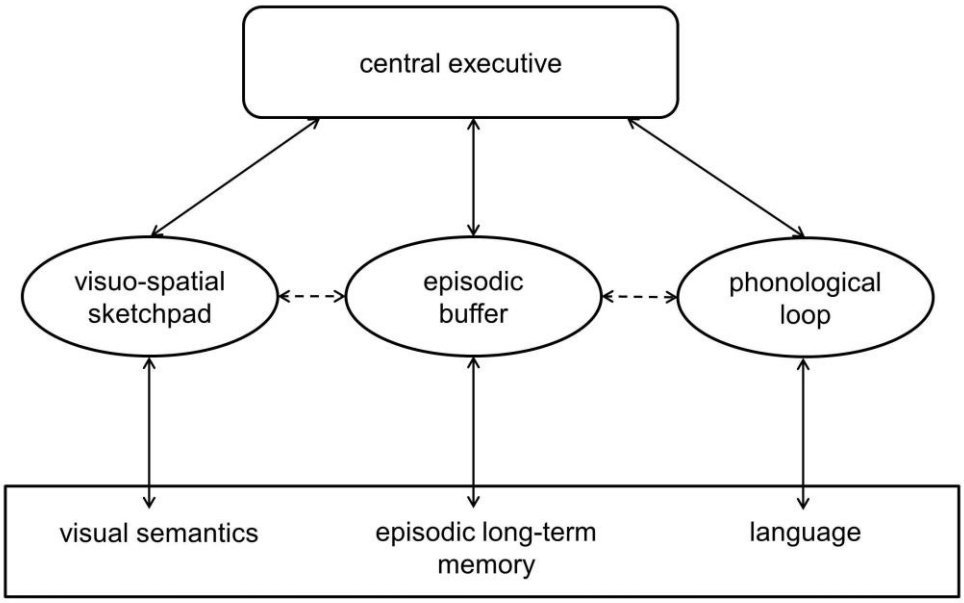

Figure 5 The multicomponent working memory model adapted from Baddeley (2003, 2010).

Therefore, E. E. Smith and Jonides (1999) as well as Miyake and colleagues (2000) investigated the fractionation of the central executive. E. E. Smith and Jonides (1999) postulated a fractionation of the central executive into five subcomponents. After reviewing neuroimaging studies that used different executive tasks, the authors assumed following five subfunctions: *Attention and inhibition* that is understood as the ability to focus attention to relevant stimuli, information, or processes while inhibiting irrelevant ones; *Task management* that encompasses the scheduling of processes in complex tasks, for example, flexibly shifting the attention between two component-tasks in order to work serially on them; *Planning* that describes the ability to coordinate a sequence of subtasks in order to achieve a certain goal; *Monitoring* that involves the evaluation and the updating of the current working memory content in order to keep track of the next steps in a sequential task. Finally, encoding new information into working memory and link this information with the place and time of appearance, describes the fifth executive function named *coding*. The authors assumed that task management as well as attention and inhibition are the rudimentary functions involved in all cognitive processes.

In contrast, Miyake and colleagues (2000) focused on three basic executive functions (see also Miyake & Friedman, 2012): Firstly, *shifting* that is understood as the ability to switch back and forth between tasks, mental sets, and cognitive operations (Monsell, 1996). Secondly, *updating* that outlines the appropriate revising of information maintained in working memory, by replacing no longer relevant contents with new ones (Morris & Jones, 1990); Thirdly, *inhibition* that is understood as the conscious suppression of automatic and dominant actions. Each function was operationalized by three different tasks, known to tap into the respective executive function. The aim of the study was to investigate the separation of those three functions. Therefore, a large sample of healthy participants was asked to perform nine executive tasks (three of them tap into one executive

function) as well as four complex tasks (encompassing multiple executive functions). Miyake and colleagues (2000) computed a confirmatory factor analysis and a structural equation model and compared multiple possible models (e.g., all three executive functions represent one latent dimension, two executive functions but not the third function share one latent dimension, and each executive function is independently from each other) with the full postulated model (i.e., three latent variables, each representing one of the three executive functions, correlating with each other). The authors found that the full model fitted the data best compared with the other models. This indicated that the three executive functions are separable from each other, but share some underlying commonality. However, Miyake and colleagues (2000) pointed out that those three executive functions are rather basically and it is assumable that there are more *higher-level* executive functions, for example, the complex concept planning, which should be investigated.

In summary, different approaches of executive functions exist. Some of them are more generally (Norman & Shallice, 1986; Shallice & Burgess, 1991a, 1991b) assuming a fuzzy control instance, while others are more specific and describe exact executive subfunctions (Miyake, et al., 2000; E. E. Smith & Jonides, 1999) or at least suggest the existence of several subcomponents of the central executive (Baddeley, 1996, 2003; Baddeley & Logie, 1999). However, these approaches are not contradictory, but rather reflect a broad concept of executive functions and working memory: There seems to be a central executive that supervises human behavior and can be fractionated into several subcomponents. Over the years a large number of various tasks have been developed to measure the diverse components of executive functioning. Some often used measures are: the Wisconsin Task Sorting Test (WCST; Berg, 1948) or the modified version of it (MCST; Nelson, 1976; see also sections 5.3.2.3 and 6.3.2.2 for a detailed description), measuring set shifting, categorization, rule detection, and cognitive flexibility; the Color Word Interference Test (also known as Stroop Test; Bäumler, 1985; Stroop, 1935) which measures inhibition/interference control and processing speed; modified versions of the n-back task mostly applied to measure updating working memory contents, but this task requires also inhibition of false reactions (Conway et al., 2005; Owen, McMillan, Laird, & Bullmore, 2005; see also section 5.3.2.2 for a description of a 2-back task); the digit span test which is a subtest of the Wechsler Memory Scale (Härting et al., 2000) and measures short term memory (forward span) and working memory (backward span); the Go/No-Go task (Mesulam, 1985) measuring attention, inhibition, categorization, and reaction speed (for an overview see Jurado & Rosselli, 2007); the Trail Making Test (TMT) part A and B, whereby part A measures processing speed and part B cognitive flexibility/set shifting; and the Tower of London (TOL) or the Tower of Hanoi (TOH) measuring planning abilities (for a description of the last two tasks see Lezak, et al., 2004; Strauss, Sherman, & Spreen, 2006). These tasks were used, among others, in studies investigating executive functions and working memory. Moreover, they are used in order to analyze the associated neural correlates of executive functions and working memory. The following section will now give an overview about those studies.

3.2.1 Neural correlates of executive functions and working memory

It is generally accepted that executive functions and working memory are associated with frontal lobes (Burgess & Shallice, 1996; Cabeza, Dolcos, Graham, & Nyberg, 2002; Cabeza & Nyberg, 2000; Müller & Knight, 2006; Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Shallice, 1982; Stuss & Benson, 1984). Especially studies with patients suffering from lesions in prefrontal areas demonstrated impairments in functions associated with the SAS (Shallice, 1982; Shallice & Burgess, 1991a, 1991b). However, over the years research revealed that

different brain areas are involved in working memory and executive functions (for detailed reviews about neural correlates of working memory and executive functions see Baddeley, 2003; Jurado & Rosselli, 2007; Royall et al., 2002; E. E. Smith & Jonides, 1997).

Based on the working memory model of Baddeley and Hitch (1974) and its further development (Baddeley, 2003, 2010), it was found that the phonological loop is more associated with the left hemisphere and the tempoparietal region while the visuo-spatial sketchpad is associated with both sides: on the right with the occipital and inferior frontal region during spatial processing and on the left side with the inferotemporal regions during object processing (E. E. Smith & Jonides, 1997; E. E. Smith, Jonides, & Koeppe, 1996; E. E. Smith et al., 1995). Concerning the central executive there seems to be an allocation between the buffering component (i.e., encoding and retrieval of information into working memory; c.f. Baddeley, 2000) and the executive component (which maintains and processes the information; c.f. Baddeley & Hitch, 1974): The buffering component is associated with posterior parietal regions and the executive component is associated with prefrontal regions (Awh et al., 1996; J. D. Cohen et al., 1997; Gathercole, 1994; Paulesu, Frith, & Frackowiak, 1993). Besides those brain regions several studies found other specific brain regions to be involved in certain working memory processes: Studies using fMRI (see section 4.3.4 for detailed information) and EEG (for measuring ERPs) in patients and healthy control samples demonstrated the general involvement of the basal ganglia in conjunction with the PFC in filtering irrelevant information (Baier et al., 2010; McNab & Klingberg, 2008; Voytek & Knight, 2010); whereby in particular the basal ganglia seem to be responsible for hindering irrelevant information to enter working memory, while prefrontal regions are engaged in maintaining information available (Baier, et al., 2010). Thus, it is reasonable that the conjunction of both regions is relevant in working memory capacity (McNab & Klingberg, 2008). Regarding the association of prefrontal regions with working memory, the meta-analyses of Wager and Smith (2003) revealed a detailed allocation of prefrontal regions: Superior prefrontal regions seem to be more involved in maintaining the information over a certain timeframe, while ventral prefrontal regions may be more activated during manipulation of information. Moreover, Cools, Gibbs, Miyakawa, Jagust, and D'Esposito (2008) demonstrated that besides the general involvement of the basal ganglia, in particular the striatum (composed of caudate nucleus and putamen), appears to be involved in working memory capacity. The authors found that subjects with high working memory capacity have a high dopamine synthesis in the striatum, whereas low dopamine synthesis was found in subjects with low working memory capacity. The involvement of the cerebellum in working memory processes was also demonstrated (Hautzel, Mottaghy, Specht, Müller, & Krause, 2009; Thürling et al., 2012). Using a 7-Tesla (T) fMRI system Thürling and colleagues (2012) supported the findings by Hautzel and colleagues (2009) that the cerebellum is not only activated in the phonological loop as was suggested before (E. E. Smith & Jonides, 1997; E. E. Smith, et al., 1996) but also in processes of the central executive. Further research groups revealed the involvement of the hippocampus, which establishes semantic associations by binding multiple information (Henke, Weber, Kneifel, Wieser, & Buck, 1999; K. J. Mitchell, Johnson, Raye, & D'Esposito, 2000; Schacter & Wagner, 1999). Some studies found also the amygdala to be integrated in working memory processes (Schaefer et al., 2006; Schaefer & Gray, 2007). However, a recent study found that paradoxically damage of the amygdala leads to better working memory capacity (Morgan, Terburg, Thornton, Stein, & Van Honk, 2012), questioning the possible role of the amygdala in working memory.

Besides studies investigating the underlying neural correlates of working memory in general, there are also studies examining the brain regions activated during certain subcomponents of the executive functions. Commonly the dlPFC is associated with executive functions (Alvarez & Emory, 2006; Cummings, 1995; Royall, et al., 2002; E. E. Smith & Jonides, 1997). Additionally it was found to be activated in several subfunctions, such as planning (e.g., Lazeron et al., 2000 using the TOL), attentional control (e.g., Kaufmann et al., 2005 using the Stroop test), in verbal or non-verbal fluency (Frith, Friston, Liddle, & Frackowiak, 1991; Jahanshahi, Dirnberger, Fuller, & Frith, 2000), and in cognitive flexibility (e.g., Lie, Specht, Marshall, & Fink, 2006; Nagahama et al., 2001 using the WCST); whereby Lie and colleagues (2006) point out that the activity in the dlPFC might be related to the executive demand of a task. The subfunction inhibition was found to be associated with orbitofrontal regions: Patients with lesions in this area seem to be impaired in inhibition of inappropriate behavior (Barkley, 1997; Cummings, 1995). Moreover, studies found the ACC (Lie, et al., 2006) as well as subcortical structures, such as the thalamus (Paulesu, et al., 1993) and the dorsal part of the striatum (Fassbender et al., 2004; Owen, Doyon, Petrides, & Evans, 1990) to be activated in various subfunctions. The ACC as well as the striatum, as part of the basal ganglia, are additionally known to be involved in neural circuits connecting frontal, posterior, and subcortical areas (Alexander, DeLong, & Strick, 1986; Collette & Van der Linden, 2002), demonstrating the interplay of different brain areas in executive functions (c.f. Alvarez & Emory, 2006).

In summary, it was shown that frontal, as well as parietal, and subcortical regions are differentially involved in working memory and executive processes, supporting the multicomponent model by Baddeley (2003, 2010). It appears that even though neural networks connecting frontal, parietal, and subcortical areas are activated during executive processes, a prominent role belongs to the dlPFC. The following sections will now present studies examining the role of cognitive processes, in particular working memory and executive functions in decision making.

3.2.2 Underlying cognitive processes in decision making

Cognitive processes are postulated to be involved in decision making under ambiguity and risk (see section 3, Figure 1 and Figure 2). However, the role of cognitive processes seems to differ between both kinds of decision making. In decision making under ambiguity a close connection with affective processes is suggested: Somatic markers are assumed to reinforce the activation of working memory and attention, which facilitates the preselection of information, leading to a representation of only profitable options for decision making (Bechara & Damasio, 2005). In contrast, Brand and colleagues (2006) assumed that even though affective and cognitive processes might interact in decisions under risk, an advantageous decision can also be made by relying solely on cognitive processes. Over the years of research many studies were conducted to investigate the potential role of working memory, executive functions, and further cognitive processes in both kinds of decision making. The following sections will summarize the findings (decisions under ambiguity: section 3.1.2.1, decisions under risk: section 3.1.2.2).

3.2.2.1 The role of cognitive processes in decision making under ambiguity

In order to determine the role of working memory in decision making under ambiguity, Bechara, Damasio, Tranel, and Anderson (1998) compared the performance in working memory tests (two kinds of delayed tasks)

as well as in the IGT (for a brief description of this task see Table 1) between patients with lesions in the dlPFC (a brain region which is associated with working memory functions, see section 3.2.1) and patients with lesions in the vmPFC (a brain region which is especially associated with decision making under ambiguity, see sections 3.1.2 and 3.3). The results revealed an asymmetrical relationship between working memory and decisions under ambiguity: For the performance of working memory it is negligible whether or not the subjects have impairments in decision making; but decision-making performance is negatively influenced by impairments in working memory. Hinson, Jameson, and Whitney (2002) supported the assumption that working memory is involved in decision making under ambiguity: They demonstrated that the performance of the IGT diminished under additionally working memory load (see also chapter 3.4.1.4.1 for detailed information and other dual-tasking studies) and that anticipatory SCRs were only developed in non-load conditions. However, according to Baddeley and colleagues (2003) working memory is a multicomponent system (c.f. section 3.2) and thus it stayed unclear which aspects of working memory may have been involved in IGT performance: The load task used by Hinson and colleagues (2002) consisted of remembering a mixed sequence of digits while making a decision. This task could have used resources of the central executive and therefore led to diminished decision-making performance. Otherwise, it could have occupied the phonological loop due to the rehearsing of the digits (Jameson, Hinson, & Whitney, 2004). To estimate whether all or a part of the working memory load was due to the disruption of the phonological loop, Jameson and colleagues (2004) used in addition to the digit maintaining task an articulatory suppression task. In this task participants had to say the word "the" while making a decision, which leads to an occupation of the phonological loop. The authors found that the performance of the IGT was only diminished when the digit-maintaining condition was performed in parallel. Consequently, they suggested that the cognitive resources required for the IGT affect the central executive and not the phonological loop. A study by Bechara and Martin (2004) supported those findings by demonstrating the involvement of working memory in the IGT. The authors found again the asymmetry of decision making under ambiguity and working memory, as it was suggested by Bechara and colleagues (1998). Beyond these findings, Bechara and Martin (2004) assumed that poor working memory capacity influences decision making under ambiguity not because of problems with the storage (buffering) processes of working memory but rather with executive processes of working memory (see section 3.2 for detailed information of the concept of working memory).

Findings of studies analyzing the relationship between executive functions and ambiguous decision making are heterogeneous: Some studies demonstrated relations between executive functions (e.g., set-shifting and inhibition) and IGT performance (e.g., Labudda, et al., 2009; Verdejo-García, Rivas-Pérez, Vilar-López, & Pérez-García, 2007), others did not (e.g., Barry & Petry, 2008; Euteneuer, et al., 2009; Sinz, et al., 2008). The study by Brand, Recknor, Grabenhorst, and Bechara (2007) offers another possible explanation. The authors supposed that executive functions become more relevant for advantageous decision making in the IGT when the rules of this task become more explicit due to implicit learning (i.e., during the conceptual period, the last 20 trials of the IGT; c.f. Bechara, et al., 1997). Therefore, they divided the IGT into five separated blocks of 20 trials and analyzed whether each block correlated differentially with specific executive functions as measured with the WCST (e.g., categorization, cognitive flexibility, and set-shifting; for a description of this task see sections 5.3.2.3 and 6.3.2.2). Brand, Recknor, and colleagues (2007) found that the last three blocks of the IGT correlated positively with the WCST. Moreover, there was a positive relationship between the last three blocks and the GDT performance. These findings may implicate that in the last blocks of the IGT the conditions change

and approach progressively decision making under risk. In these conditions the rules are well known and executive functions are involved (Brand, et al., 2006). In order to enlighten the heterogeneous findings concerning the relationship between decision making under ambiguity, executive functions, working memory, and cognitive ability, a recent review analyzed several studies in regard to this topic (Toplak, Sorge, Benoit, West, & Stanovich, 2010). The authors concluded that although the analyzed studies are heterogeneous about the relationship between executive functions, working memory, cognitive ability, and decision making under ambiguity, the majority of the analyzed studies reported a non-significant relationship. Furthermore, even the reported "significant associations were modest in size with wide confidence intervals" (Toplak, et al., 2010, p. 577), indicating that the variance of decision-making performance in the IGT is little captured by executive functions and working memory.

Overall, the pattern of the role of executive functions and working memory in decision making under ambiguity is not clear: While working memory performance seems to affect decision making, the relationship with executive functions lacks of distinctness. However, it seems that executive functions may be less involved in decisions under ambiguity but more under risk (Brand, Recknor, et al., 2007; Toplak, et al., 2010). Thus, the next section will address the role of executive functions and working memory in decisions under risk.

3.2.2.2 The role of cognitive processes in decision making under risk

A great number of studies interested in decision making under risk presented an involvement of working memory and executive functions. An overview of exemplarily studies demonstrating relationships between decisions under risk and working memory or executive functions will be given in Table 2. Please note that this table has no claim of completeness. This table is arranged according to the cognitive functions measured by the tests mentioned in the studies and in respect to the decision-making task used. As can be seen in Table 2 various studies found support for the assumed positive relationship between working memory and decisions under risk (c.f. Brand, et al., 2006). Moreover, the correlations between executive functions and decision making are moderate to high and support the assumption that superior executive functions are associated with advantageous decision making under risk. This is in contrast to the only modest size of correlations between decision making under ambiguity and executive functions found by Toplak and colleagues (2010).

Table 2 Correlations between decision-making tasks and working memory or various executive functions.

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Working memory (updating, manipulating, or maintaining of information)			
BART	Digit span	In heavy drinkers:	Ashenhurst, Jentsch and Ray (2011)
adjusted average pumps (without pumps leading to an explosion)	total score	$r = .345$, $p < .001$	
post failure mean pumps		$r = .318$, $p < .001$	
GDT	2-back task	In the control group:	Drechsler, Rizzo, and Steinhausen (2007)
high-risk choices (12 rounds of GDT)	omissions	$r = -.539$, $p = .008$	
high-risk choices (18 rounds of GDT)		$r = -.718$, $p \leq .001$	
GDT	Digit span	In patients with TLE:	Labudda et al. (2009)
one single number	backwards score	$r = .46$, $p = .04$	
GDT	3-back task	In the control group:	Schiebener, Wegmann, Pawlikowski, and Brand (2013)
net score	percentage of correct responses	$r = .47$, $p = .01$	
GDT	n-back tasks	In the GDT group:	Starcke et al. (2011)
net score	percentage of correct responses in 1-back and 2-back task	$r = .23$, $p < .05$	
PAG-task	Digit span	In one subgroup (patients with RTLE):	Bonatti et al. (2009)
frequency of gambles in the low probability condition	backwards score	$r = -.671$, $p = .024$	
PAG-task	Digit span	In older people:	Zamarian et al. (2008)
frequency of strategy changes on probability decreasing trials	backwards score	$r = .429$, $p = .011$	
Attention and inhibition (interference susceptibility/control)			
CGT	PASAT	In patients with MS:	Simoni et al. (2012)
deliberation time	number of correct answers	$r = -.364$; $p = .002$	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Attention and inhibition (interference susceptibility/control)			
GDT	CWIT	In the GDT non-feedback group:	Brand (2008)
one single number	time needed on the interference trial	ρ = .37, p = .04	
GDT	CWIT	In patients with BN:	Brand, Franke-Sievert, Jacoby, Markowitsch, and Tuschen-Caffier (2007)
high-risk choices	time needed on the interference trial	r = .594, p = .042	
GDT	CWIT	All participants included (healthy participants):	Brand, Heinze, et al. (2008)
net score	time needed on the interference trial	ρ = -.376, p < .05	
GDT	Continuous performance task of the TAP	In patients with ADHD:	Drechsler et al. (2007)
financial outcome (12 rounds of GDT)	commission errors	r = -.49, p = .026	
GDT	HCST	In patients with paranoid schizophrenia:	Fond et al. (2012)
low-risk choices	errors	r = -.36, p = .019	
PAG-task	Go/No-Go task	In the control group:	Bonatti et al. (2008)
frequency of gambles in the low probability condition	number of correct go trials	r = -.475, p < .05	
Cognitive flexibility (set-shifting and perseveration tendency)			
BART	WCST	In patients with AA:	J. A. Campbell, Samartgis, and Crowe (2013)
adjusted average pumps (without pumps leading to an explosion) in the third block (trial 30-45)	non-perseverative errors[a]	r = .54, p < .05	
	correct responses	r = .45, p < .01	
		In the control group:	
	non-perseverative errors[a]	r = .65, p < .01	
	perseverative errors[a]	r = .60, p < .05	
	correct responses	r = .61, p < .01	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Cognitive flexibility (set-shifting and perseveration tendency)			
GDT	MCST	In the GDT group:	Brand (2008)
one single number	non-perseverative errors	$r = .41$, $p = .023$	
GDT	TMT B	In patients with BN:	Brand, Franke-Sievert, et al. (2007)
high-risk choices	time needed	$r = .572$, $p = .033$	
GDT	MCST	In patients with KS:	Brand, Fujiwara, et al. (2005)
high-risk choices	correct responses	$\rho = -.76$, $p < .001$	
	non-perseverative errors	$\rho = .71$, $p < .001$	
GDT	MCST	All participants included (healthy participants):	Brand, Heinze, et al. (2008)
one single number	correct responses	$\rho = -.315$, $p < .05$	
	non-perseverative errors	$\rho = .319$, $p < .05$	
GDT	MCST	In patient with PG:	Brand, Kalbe, et al. (2005)
high-risk choices	correct responses	$r = -.515$, $p = .009$	
	non-perseverative errors	$r = .499$, $p = .011$	
	perseverative errors	$\rho = .501$, $p = .011$	
GDT	MCST	In patients with PD:	Brand et al. (2004)
high-risk choices	non-perseverative errors	$r = .51$, $p = .021$	
GDT	MCST	In the GDT group:	Brand, Laier, et al. (2009)
net score	non-perseverative errors	$r = -.27$, $p \leq .05$	
	TMT B	In the GDT non-feedback group:	
	time needed	$r = -.37$, $p \leq .01$	
GDT	MCST	In patients with KS (independent of task version):	Brand, Pawlikowski, et al. (2009)
one single number	perseverative errors[a]	$r = -.33$, $p = .02$	
GDT	MCST	In the control group:	Brand, Roth-Bauer, Driessen, and Markowitsch (2008)
one single number	perseverative errors	$r = .480$, $p < .05$	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Cognitive flexibility (set-shifting and perseveration tendency)			
GDT	MCST	Including a subgroup of (healthy) participants performing the MCST:	Brand and Schiebener (2013)
net score			
	categories	$r = .21$, $p \leq .001$	
	non-perseverative errors	$r = -.26$, $p \leq .001$	
	perseverative errors	$r = -.24$, $p \leq .001$	
one single number		$r = -.35$, $p \leq .001$	
		$r = .38$, $p \leq .001$	
		$r = .35$, $p \leq .001$	
GDT	TMT B	In patients with AD	Delazer, Sinz, Zamarian, and Benke (2007)
frequency of shifts between high-risk and low-risk choices	time needed	$r = .697$, $p = .012$	
GDT	MCST	In patients with PD:	Euteneuer et al. (2009)
net score	correct responses	$r = .51$, $p = .018$	
	perseverative errors	$r = -.50$, $p = .021$	
final outcome	correct responses	$r = .56$, $p = .008$	
	non-perseverative errors	$r = -.48$, $p = .029$	
	perseverative errors	$r = -.45$, $p = .042$	
GDT	TMT B	In patients with paranoid schizophrenia:	Fond et al. (2012)
low-risk choices	time needed	$r = -.434$, $p = .005$	
GDT	VLMT	In patients with TLE:	Labudda et al. (2009)
net score	frequency of perseverations	$r = -.62$, $p < .01$	
one single number		$r = .48$, $p = .04$	
GDT	WCST	In patients with WD:	Ma et al. (2013)
high-risk choices	categories	$r = -.784$; $p = .002$	
	perseverative errors	$r = .718$; $p = .006$	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Cognitive flexibility (set-shifting and perseveration tendency)			
GDT	MCST	In the GDT with goal and anchor group:	Schiebener, Wegmann, Pawlikowski, and Brand (2012)
one single number	non-perseverative errors	$r = .57$, $p \leq .001$	
GDT	MCST	In healthy participants:	Schiebener et al. (2011)
net score	non-perseverative errors	$r = -.24$, $p \leq .05$	
one single number	categories	$r = -.35$, $p \leq .01$	
	non-perseverative errors	$r = .38$, $p \leq .01$	
	perseverative errors	$r = .28$, $p \leq .05$	
	TMT B		
	time needed	$r = .23$, $p \leq .05$	
GDT	MCST	In patients with OCD:	Starcke, Tuschen-Caffier, Markowitsch, and Brand (2010)
one single number	correct responses	$r = -.43$, $p \leq .05$	
	non-perseverative errors	$r = .45$, $p \leq .05$	
		in the control group:	
	correct responses	$r = -.47$, $p \leq .05$	
	non-perseverative errors	$r = .59$, $p \leq .05$	
GDT	TMT B	In the pooled group (patients with BPD and control participants):	Svaldi, Philipsen, and Matthies (2012)
net score	time needed	$r = -.358$, $p = .006$	
PAG-task	WCST	In the pooled group (patients with TLE and control participants):	Bonatti et al. (2009)
frequency of gambles in the low probability condition	number of categories	$r = -.295$, $p = .042$	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
Cognitive flexibility (set-shifting and perseveration tendency)			
PAG-task	TMT B	In patients with TBI	Bonatti et al. (2008)
frequency of gambles in the low probability condition	time needed	$r = .599$, $p < .05$	
		In the control group:	
		$r = .491$, $p < .05$	
		In patients with TBI:	
frequency of gambles in the high probability condition		$r = -.498$, $p < .05$	
PAG-task	TMT B	In patients with PD:	Delazer, Sinz, et al. (2009)
frequency of gambles in the low probability condition	time needed	$r = .473$, $p = .041$	
	OMO		
	errors	$r = .675$, $p = .001$	
frequency of gambles in the high probability condition	OMO	In patients with PDD:	
	errors	$r = -.523$, $p = .026$	
PAG-task	MCST	In healthy participants:	Schiebener et al. (2011)
frequency of gambles in the low probability condition	categories	$r = -.24$, $p \leq .05$	
	non-perseverative errors	$r = .22$, $p \leq .05$	
	perseverative errors	$r = .30$, $p \leq .01$	
frequency of gambles in the moderately low probability condition	perseverative errors	$r = .23$, $p \leq .05$	
PAG-task	TMT B	In older people:	Zamarian et al. (2008)
frequency of gambles in the low probability condition	time needed	$r = -.414$, $p = .017$	
CGT	TOL	In patients with HD:	Watkins et al. (2000)
time taken to chose	time to first response	$r = .55$; $p < .01$	
bet size		$r = -.59$; $p < .01$	

Decision-making task	Task used to measure facets of executive functions	Correlation between both tasks	Study
		Planning	
GDT	TOH	In the GDT group:	Brand (2008)
one single number	time needed	r = .66, p < .001	
	moves	r = .49, p = .006	
GDT	TOH	In patients with OD:	Brand, Roth-Bauer, et al. (2008)
net score	time needed	r = -.689, $p \leq .01$	
	moves	r = -.603, $p \leq .01$	
one single number	time needed	r = .734, p ≤ .01	
	moves	r = .749, $p \leq .01$	
	errors	r = .494, $p \leq .05$	
		In the control group:	
one single number	moves	r = .643, $p \leq .01$	
PAG-task	FAB	In patients with mild DAT:	Sinz et al. (2008)
frequency of gambles in the low probability condition	subtest of motor programming	r = -.502, p < .05	
frequency of gambles in the high probability condition	subtest of motor programming	r = .594, p < *.01*	

Note. The MCST and the WCST are both complex executive functions tasks that measure a broad range of executive functions (see e.g., Jurado & Rosselli, 2007; Miyake, et al., 2000). In this table, it is assigned to cognitive flexibility, the most named executive function in relation with WCST/MCST in the papers. *Decision making tasks:* BART = Balloon Analogue Risk Task; CGT = Cambridge Gamble Task; GDT = Game of Dice Task; PAG = Probability-Associated Gambling task. *Tasks associated with executive functions:* ACT = Auditory Consonant Trigram (for a description of this task see Brown, 1958); Cued Go/No-Go task (for a description of this task see Derefinko et al., 2008); CWIT = Color Word Interference Test; FAB = Frontal Assessment Battery (for a description of this battery see Dubois, Slachevsky, Litvan, & Pillon, 2000); HCST = Hayling Sentence Completion Task (for a description see Belleville, Rouleau, & Van der Linden, 2006); MCST = Modified Card Sorting Test; OMO = Odd-Man-Out (for a description of this task see Flowers & Robertson, 1985); TAP = Test of Attentional Performance (see Zimmermann & Fimm, 2002); TMT B= Trail Making Test part B; TOH = Tower of Hanoi; VLMT = Verbal Learning and Memory Test (for a description of this task see Helmstaedter, Lendt, & Lux, 2001); WCST = Wisconsin Card Sorting Test. *Psychiatric and neurological disorders:* AA = alcohol abuse; AD = Alzheimer's disease ADHD = attention deficit/hyperactivity disorder; BED = binge eating disorder; BN = bulimia nervosa; BPD = borderline personality disorder; DAT = dementia of Alzheimer's type; HD = Huntington's disease; KS = Korsakoff's syndrome; LTLE = left temporal lobe epilepsy; MS = multiple sclerosis; PD = Parkinson's disease; PDD = Parkinson's disease dementia; PG = pathological gambling; RTLE = right temporal lobe epilepsy; TLE = temporal lobe epilepsy. *Further abbreviations:* n.s. = not significant; [a]t-scores of the MCST data. Note that higher t-scores represent better MCST-performance.

Besides those studies providing a correlation between decision making under risk and executive functions, studies demonstrating that patients suffering from impairments in executive functions (compared with healthy control participants) have increased problems in making advantageous decisions, too, support the assumption that superior executive functions are important for decisions under risk (e.g., Brand, et al., 2006). This was shown for example, in patients with alcohol dependence (e.g., Y.-T. Kim, Sohn, & Jeong, 2011),

schizophrenia (Reddy et al., 2014), borderline personality disorder (e.g., Bazanis et al., 2002), Parkinson's disease (e.g., Torta, Castelli, Zibetti, Lopiano, & Geminiani, 2009), binge eating disorder (e.g., Svaldi, Brand, & Tuschen-Caffier, 2010), Urbach-Wiehte disease (e.g., Brand, Grabenhorst, et al., 2007), hoarding behavior (e.g., Grisham, Norberg, Williams, Certoma, & Kadib, 2010), mild cognitive impairment (e.g., Zamarian, Weiss, & Delazer, 2010), and in patients using cannabis (e.g., Grant, Chamberlain, Schreiber, & Odlaug, 2012) or suffering from sleep deprivation (e.g., Ståhle et al., 2011).

Although the pattern of involvement of executive functions and working memory in decision making under risk appears to be more clear than in decisions under ambiguity, there are also studies which did not find such a relationship (e.g., Bogg, Fukunaga, Finn, & Brown, 2012; Fishbein et al., 2005; Matthies, Philipsen, & Svaldi, 2012; Passetti, Clark, Mehta, Joyce, & King, 2008; Roiser et al., 2009; Wu, Liu, Hallett, Zheng, & Chan, 2013). Some of these studies argue that no relationship was found because the patient group investigated, appears to have affective dysfunctions rather than executive ones, which supports again the assumption of the involvement of cognitive and affective processes in decision making under risk: For example, Fishbein and colleagues (2005) found impaired decision making, as measured with the CGT (for a brief description of the task see Table 1), in drug abusers, although no impairments on executive tasks were obvious. The authors argued that the additional changes in affect-regulation, which were found during decision making (i.e., lower increase in SCRs), appear to be associated with risky decisions. Similar, Pacetti and colleagues (2008) investigated opiate dependent people demonstrating impairments in the CGT and IGT (for a brief description of these tasks see Table 1) but not in executive measurements. The authors discussed those findings relying on the fact that both decision-making tasks are more associated with the OFC (neural correlates of decision making are discussed in section 3.3), an area also known to be involved in breakdown of self-control processes in drug abusers (Goldstein & Volkow, 2002) and affective processing (see section 3.1.1). Roiser and colleagues (2009) investigated cognitive functions in patients with bulimia nervosa. They divided the cognitive functions in rather *hot* (affective-dependent) functions involved in the CGT and rather *cold* (affective-independent) functions, for example, planning and working memory. The authors revealed that patients with bulimia nervosa had impairments in hot but not in cold cognitive functions. To these findings and assumptions that affective processes in decision making seem to be impaired resulting in inferior decision-making performance, matches also the study by Wu and colleagues (2013). They demonstrated no impairments on the GDT (for a brief description of this task see Table 1) in patients with bulimia nervosa and binge eating disorder, but in executive functions such as motor inhibition. Wu and colleagues (2013) argued that these patients did not show impaired decision making because of their higher sensitivity to punishment (negative affective feedback).

On the contrary, other studies that did not find a relationship between executive functions and decision making under risk provide other cognitive functions to be involved. For example, Bogg and colleagues (2012) investigated "cognitive control via reward-seeking medial prefrontal cortex activity as a common neuro-functional marker of excessive alcohol consumption, trait inhibition, and reduced cognitive capacity" (Bogg, et al., 2012, p. 116). The authors used the BART (for a brief description of this task see Table 1) to operationalize reward-seeking during fMRI, the sensation seeking scale (Zuckerman, 1979) to measure trait inhibition, and a working memory and intelligence task to measure cognitive capacity. They found that increased alcohol consumption in young adults, accompanied by increased disinhibition and decreased logical reasoning but not lower working memory, leads to down-regulation of cognitive control via the medial prefrontal cortex during reward-seeking choices, in case the probability of a loss increases. Using the GDT Matthies and colleagues (2012) did not find a relationship between decision making and executive functions in patients with ADHD.

However, they revealed that patients, who chose more often the high-risk options in the GDT, also had impaired strategy application and were not able to learn from feedback.

The involvement of further cognitive processes in decisions under risk, such as logical reasoning and the application of cognitive strategies was also found in various other studies (Brand, Heinze, et al., 2008; Brand, Laier, et al., 2009; Deakin, Aitken, Robbins, & Sahakian, 2004). Brand, Heinze, and colleagues (2008) were interested in the question whether participants who apply calculative decision strategies perform the GDT superior to participants applying intuitive decision strategies. The authors found that subjects, who pursued calculative strategies, chose the low-risk options more often in that task. In contrast, subjects who decided more intuitively chose the disadvantageous options more frequently. Moreover, intuitive deciders switched between the high-risk and low-risk options more often compared with deciders applying a calculative strategy. Thus, Brand, Heinze, and colleagues concluded that subjects who already have calculated which options are the advantageous ones do not need to try each option in order to learn from feedback which options are the low-risk options. Additionally, the authors found that applying calculative strategies was associated with executive functions, supporting their important role in decision making under risk and their connections with other cognitive functions. In the study by Brand, Laier, and colleagues (2009) the important role of cognitive strategies but also of logical reasoning for advantageous decision making was again found. In this study the original GDT and a GDT without feedback was administered. In this modified version participants had to decide without the opportunity to learn from feedback. Comparing the performance of the two tasks Brand, Laier, and colleagues (2009) found that subjects decided more advantageously in the original version of the GDT, which provides feedback. However, subjects with superior logical reasoning abilities and subjects who applied calculative strategies still demonstrated superior decision-making performance even though no feedback was provided. Those findings emphasize the superior role of cognitive abilities compared with feedback processing in risky decision making: Even though both routes (cognitive and affective) are involved in the decision-making process (Brand, 2008; Brand, et al., 2006), the cognitive route is able to compensate the missing or impaired (affective) feedback route.

A further interesting finding was that different cognitive functions may compensate each other in order to provide superior decision-making performance. This means that participants with impairments of one cognitive function may still be able to decide advantageously as long as other important cognitive functions remain intact (Schiebener, et al., 2011). Schiebener and colleagues (2011) found that besides superior executive functions, both logical thinking and probability processing abilities (as measured in the PAG-task, for a brief description of this task see Table 1) led to advantageous decision-making performance. Furthermore, in a moderated regression analysis it was demonstrated that if two cognitive functions (e.g., executive functions and probability processing or logical thinking and probability processing) were low, participants chose the high-risk options more often. In contrast, if one cognitive function was still high, participants chose advantageously. Thus, the authors assumed that "impairments in only one component […] are likely to be compensated and to be evident in performance in the GDT" (Schiebener, et al., 2011, p. 14).

Moreover, cognitive functions in particular executive functions seem to be capable of compensating negative external influences such as goal setting and anchors (Schiebener, et al., 2012). Schiebener and colleagues (2012) investigated the possible influences of anchor effects (e.g., comparison values of possible but improbably high final outcomes) and self-set goals (i.e., participants had to set final outcome goals before

performing the GDT) on decision-making performance in the GDT. The authors found that those anchors caused riskier decision making, but that only high self-set goals correlated negatively with decision making (for a detailed information about the influence of self-set goals on decision making under risk please be referred to Schiebener, Wegmann, Pawlikowski, & Brand, 2014). Furthermore, Schiebener and colleagues (2012) showed that participants with superior executive functions, who strived for goals, were less impaired by external anchors than participants with low executive functions. Those findings imply that it depends on the cognitive abilities (in particular executive functions) whether situational influences affect decision making under risk. This applies also for positive situational influences like explicit and factual advice (Schiebener, Wegmann, Pawlikowski, & Brand, 2013). In the study by Schiebener and colleagues (2013) participants had the opportunity to purchase one of four different advices before performing the GDT: getting expanded information about the GDT, obtain information about the probabilities associated with each alternative, receiving advice about the advantageous options, or acquire two test trials of the GDT. The authors found that those advices itself supported decision making advantageously. However, it depended on the cognitive abilities whether such advice was needed: Participants with high executive functions and working memory abilities did not need advice to decide advantageously, but in participants with low executive functions and working memory abilities advice improved decision-making performance.

Overall, the studies emphasize the important role of executive functions, working memory, and further cognitive abilities in decision making under risk. In particular, it seems that executive functions are connected to various cognitive abilities with which they work in concert or compensate each other in order to enable the subject to decide advantageously. Compared with decisions under ambiguity the essential involvement of executive functions in decision making under risk seems to be clearer and less doubtable (c.f. section 3.2.2.1). So far, the chapters gave an overview about the underlying affective and cognitive processes in decision making under ambiguity and risk as postulated in the decision-making models (c.f. section 3, Figure 1 and Figure 2). The following section will summarize neuroimaging studies investigating the underlying neural correlates of decision making.

3.3 Neural correlates of decision making

Affective and cognitive processes, which are associated with various different brain regions (c.f. sections 3.1.1 and 3.2.1 for brain regions involved in affective and cognitive processing and also section 3.1.2 for brain regions associated with the origin of somatic markers), are involved in decision making under ambiguity and risk. Thus, it is assumable and in line with lesion studies mentioned in several sections before (see sections 3.1.2.1, 3.1.2.2, 3.2.2.1, and 3.2.2.2) that these brain regions are, at least in parts, also involved in decision making under ambiguity and risk. In the following exemplarily neuroimaging studies investigating activated brain regions during decision-making performance in healthy participants are discussed.

Investigating the neural correlates of decision making under ambiguity Ernst and colleagues (2002) used positron emission tomography (PET) with ^{15}O-labeled water in male and female healthy participants during IGT performance (see Table 1 for a detailed description of this task). PET provides three-dimensional images of brain activation. In contrast, to fMRI (see section 4.3.4), in PET radioactive tracers are used to detect blood flow, glucose consumption or neurotransmitter (e.g., dopamine) receptor binding (for detailed information about PET see Wager, Hernandez, Jonides, & Lindquist, 2007). Ernst and colleagues (2002) revealed activation during the IGT compared to a control task without the decision making aspect in the OFC, the dlPFC, the ACC,

the insular cortex, the parietal cortex, the thalamus and the cerebellum. In a subsequent fMRI study by Fukui, Murai, Fukuyama, Hayashi, and Hanakawa (2005) it was shown that in particular the net score of the IGT positively correlated with the magnitude of the activation in the medial PFC during disadvantageous decisions. Northoff et al. (2006) revealed a correlation between an increase in activity in particular the vmPFC (specific part of the medial PFC) IGT performance. The vmPFC was activated during a task which was associated with unexpected affective judgments. The positive correlation between this activation and IGT performance indicates that an increased activation in an area associated with unexpected affective judgments is associated with advantageous decisions under ambiguity. In contrast to these studies, which investigated the IGT as a whole, Lin, Chiu, Cheng, and Hsieh (2008) examined neural correlates of certain phases of the IGT and found following associations: The insula cortex and the lentiform nucleus (part of the basal ganglia, comprised the putamen and the globus pallidus) were activated during the anticipation phase (decision driving) and may therefore play an essential role in long-term guidance of a decision. The inferior parietal lobule in contrast was activated during the outcome phase (value representation) and thus might participate in evaluation processes of consequences. In the study by Chiu and colleagues (2008), the medial PFC was again activated during the high punishment contingencies (i.e., disadvantageous decisions; which is comparable with the findings by Fukui, et al., 2005). This was also found in the study by Lawrence, Jollant, O'Daly, Zelaya, and Phillips (2009). Moreover, the authors found also the lateral OFC and the insular cortex associated with the anticipation of punishment in disadvantageous trials. In contrast, striato-thalamic regions (e.g., caudate nucleus, nucleus accumbens, and thalamus, which are all parts of the basal ganglia) were rather associated with reward (win) than punishments (loss). Beyond that Lawrence and colleagues (2009) revealed an involvement of the lateral OFC and the pre-supplementary motor area in learning processes, whereas the vmPFC appears to be associated with more general task components such as monitoring of rewards and response-reinforcement over trials. Furthermore, they found that these activated brain regions (except the striato-thalamic regions) along with the secondary somatosensory cortex correlated positively with IGT performance. The insular cortex as well as the secondary somatosensory cortex are moreover, associated with the generation or processing of somatic markers, which supports the assumption of the activation of somatic markers in decision making (e.g., Bechara, et al., 1999). This was also demonstrated in the study by Li, Lus, D'Argembeau, Hg, and Bechara (2010) who set out to investigate the underlying neural circuitry of somatic markers and decisions under ambiguity. Besides the involvement of the insular cortex they also reported activation in the dlPFC, the vmPFC, the supplementary motor area, and the ventral striatum. The authors defined the ventral striatum as "striatum below the anterior commissure" (Li, et al., 2010, p. 415), which in humans comprises the nucleus accumbens and is part of the basal ganglia (c.f, Pritzel, et al., 2003, p. 26). Li and colleagues (2010) suggested that these areas are all associated with different parts of the decision-making process: the dlPFC with working memory, the insula cortex with the representation of affective state, the vmPFC with the coupling of the two previous processes, and the ventral striatum and the supplementary motor area with the implementation of decisions.

Most of the brain regions activated in decisions under ambiguity were also found to be involved in certain phases of decision making under risk. For example, Rogers, Owen, and colleagues (1999) using the CGT (for a description of the task see Table 1) reported increased blood flow in the OFC (in particular the anterior part of the middle frontal gyrus and the orbital gyrus) and the rather inferior convexity of the PFC (i.e., anterior part of the inferior frontal gyrus), when participants resolve the conflict that inherent a risky decision (i.e., the most likely outcome is associated with a reduced reward compared to the less likely outcome). The authors argue that the area activated in the inferior PFC receives information from diverse cortical and limbic inputs,

whereas the OFC may rather be involved in reward processing. In a subsequent study using a modified version of the CGT (Rogers et al., 2004), they revealed that the neural activity within the ACC, the OFC, and the striatum (part of the basal ganglia comprising the caudate nucleus and the putamen) mediates the representation of reward information at different stages during a decision process. Rao, Korczykowski, Pluta, Hoang, and Detre (2008) were interested in the different activation during voluntary and involuntary risk-taking in decision making. Therefore, the authors compared activation during a BART version, in which participants had the choice do decide when to discontinue inflating and a version, in which the computer stopped inflation automatically. Overall, they reported that decision making (i.e., active choice condition) compared to the passive condition led to increased activation in the dlPFC. When taking the parametric risk levels into account, the following regions were activated during the active choice condition contrasted with the passive choice condition and thus co-varied with voluntary risk: the ventral tegmental area, several nuclei of the basal ganglia (the striatum, the nucleus accumbens, and the globus pallidus), the anterior insular cortex, the dlPFC and the ACC. Fukunaga, Brown, and Bogg (2012) examined in particular the contribution of the anterior insular cortex and the ACC to decision making under risk using also the BART. It was shown that both regions were involved in loss aversion (i.e., activated when participants discontinue to inflate the balloon). In contrast, reward seeking robustly activated the vmPFC. A recent study concentrated on the role of a fronto-striatal network (including e.g., the striatum, nucleus accumbens, amygdala, the hippocampus, and the PFC) in decision making and found an involvement of such a network in the modulation of risk-taking in the BART (Kohno et al., in press). The involvement of the dlPFC and the ACC was additionally found in an fMRI study using a paradigm similar to the GDT (Labudda et al., 2008). In this study, Labudda and colleagues contrasted a decision situation with potential incentives with a decision situation without incentives. They reported increased activation in the dlPFC, the ACC, and the posterior parietal lobe, and the lingual gyrus; an activation pattern suggesting the involvement of executive functions, conflict detection, and arithmetic operations. Due to the fact that no feedback was given potential activation of feedback processing areas could not be announced.

Overall, brain regions involved in decisions under ambiguity are also involved in decisions under risk. It rather appears to depend on the focus of the study which exact regions are in particular activated in decision making: whether the study investigated a single decision process (e.g., feedback/outcome phase vs. decision phase) or the whole decision processes not further specified or separated into phases. Figure 6 summarizes the brain regions found to be activated in decision-making performance irrespective of the decision situation (i.e., ambiguity or risk) and phase. These regions were found to be activated differentially in various patient groups compared to healthy control participants. Such activation differences were mostly associated with impaired decision making in these patient groups, for example: The activation in the medial part of OFC during high incentive trials of a card cueing task was negatively correlated with GDT performance in patients with ADHD. This indicated that a dysfunction in an area associated with reward value processing was associated with impaired decision making (Wilbertz et al., 2012). Studies using the IGT revealed neural changes in the OFC, the vmPFC, the dlPFC, the cerebellum, and in the striatum in patients with substance abuse, which were associated with more disadvantageous decision making compared to healthy controls (Bolla, Eldreth, Matochik, & Cadet, 2005; Power, Goodyear, & Crockford, 2012; Vaidya et al., 2012). Patients suffering from traumatic brain injury showed different activation in the dlPFC, the thalamus, and the hippocampus during the CGT compared to healthy controls associated with increased risky decision making (Newcombe et al., 2011), while patients with mania displayed neural activity changes in the ACC and the frontopolar region (Rubinsztein et al., 2001).

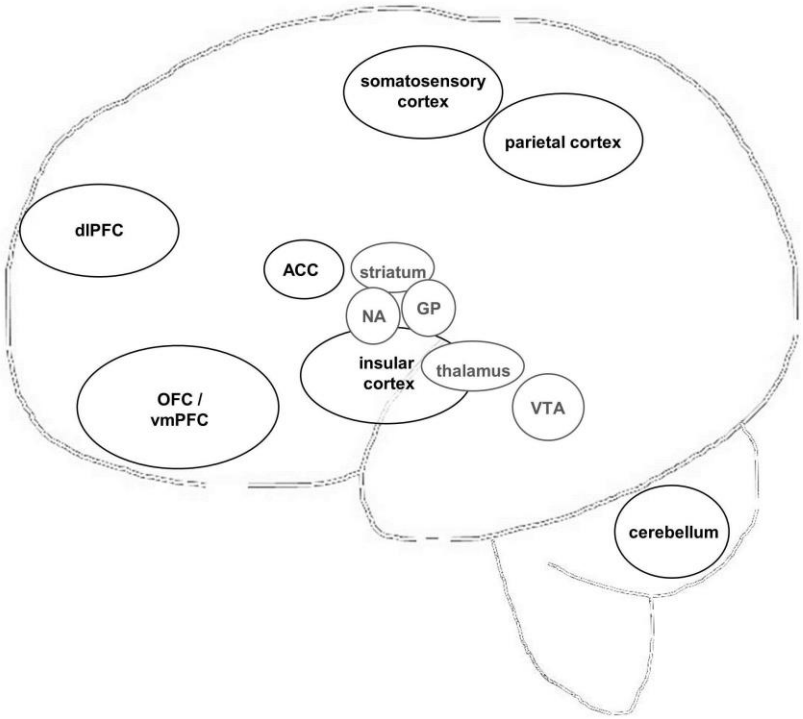

Figure 6 A simplified presentation of the activated brain regions found in various decision-making studies.
The cortical regions are colored in black and the subcortical regions are colored in grey.

In general, it appears that some brain regions are more activated during (affective) feedback processes while others are more initiated during cognitive processes in decision making. This may be in line with the finding by Gläscher and colleagues (2012). The authors applied a lesion overlap analysis (using nonparametric voxel-based lesion symptom mapping; Rorden, Karnath, & Bonilha, 2007) that takes advantage of a unique dataset, accrued over several decades in order to analyze the regional specificity of various cognitive functions in the PFC (e.g., cognitive control and valued based decision making). This dataset provided "sufficient lesions coverage in the PFC, and most other regions of the brain, to detect significant lesion-deficit relationships" (Gläscher, et al., 2012, p. 14682) on cognitive functioning. Gläscher and colleagues demonstrated two functional-anatomical systems within the PFC: One system is associated with cognitive control (e.g., response inhibition, conflict monitoring, and switching) including the dlPFC and the ACC. In contrast, the second system is associated with valued based decision making and reward learning and includes following brain regions: the vmPFC, the frontopolar cortex, and the OFC. However, it appears that both networks converge in the ACC, indicating a potential for assumed interactions between the two networks. This again may support the postulated decision-making models, in which affective as well as cognitive processes are suggested to be involved in decision-making performance (see section 3, Figure 1 and Figure 2).

To this point, the underlying cognitive and affective processes as well as the associated neural correlates of decision making were focused. The next chapter will discuss situational circumstances and their possible influence on decision-making behavior.

3.4 Situational influences on decision making from a neuropsychological perspective

Based on the discussed findings so far, it is imaginable that task-irrelevant affective processes for instance sadness, happiness or stress, which involve brain areas associated with decision making may interrupt human decision-making behavior; just as additional cognitive processes, which load on the same cognitive (neural) network as decision making. The following sections address such influences in more detail. In section 3.4.1 additional cognitive demand and its influence on decision-making performance will be addressed. This is followed by affective influences (see section 3.4.2) and stressful influences (see section 3.4.3) on decision making. At last the interaction between affective and cognitive additional demand and decision making particularly under risk will be discussed.

3.4.1 Additional cognitive demand

Affective and cognitive processes are involved in decision making under ambiguity and risk and may interact in order to realize superior decision-making performance (c.f. the decision-making models in Figure 1 and Figure 2). However, it appears that affective processes are rather essential for decisions under ambiguity while cognitive processes are predominantly involved in decisions under risk (for a detailed discussion see chapter 3.1 and 3.2). In order to further analyze these assumptions, researchers used additional executive tasks which the participants had to perform while making a decision. This leads to an additional load on the cognitive system. Researchers assumed that if cognitive processing would be essential in the decision-making process, this additional demand should lead to decreased decision-making performance (for detailed description see section 3.4.1.4). This assumption is derived from dual-process theories, which also assume two information processing modes, whereby one appears to be more comparable with the affective route and the other with the cognitive route (for reviews see Evans, 2003, 2008). Decision situations in which an additional executive task has to be performed are comparable with basic dual-tasking studies in which participants are asked to perform two tasks simultaneously. Dual-tasking situations are often used in order to investigate information processing and over the years of research different approaches arose (see section 3.4.1.1). Therefore, before reporting studies investigating the role of dual tasking in decision making under ambiguity (section 3.4.1.4.1) and risk (section 3.4.1.4.2), an overview about dual-process theories and dual-tasking approaches will be given in the upcoming section (see section 3.4.1.1). The focus of the chapter is on the involved executive functions in dual tasking. Therefore, a few studies investigating the underlying executive mechanisms of dual tasking will be briefly discussed (see section 3.4.1.2). In this context task-switching paradigms are introduced, too. These paradigms, which also consist of two concurrent tasks, were in particular developed in order to investigate executive processes in more detail (see section 3.4.1.2.1) This is followed by an overview about findings concerning the associated neural correlates of dual-tasking and task-switching paradigms (section 3.4.1.3), in order to understand which cognitive and neural mechanisms these processes share with decision-making processes and why it is of interest to investigate decision making in dual-tasking situations.

3.4.1.1 From a theoretical perspective: Dual processes and dual tasking

The assumption of two separated but interacting processing modes is in line with dual-process theories (for reviews see Evans, 2003, 2008). However, the assumption of a generic dual-process system appears to be simplified: Dual-process theorists describe these systems with various attributes and it is difficult to link them together across different dual-process theories (Evans, 2008). Evans argues that this is because while one system

is rather described as relying on single, capacity limited working memory resources, the other system is usually referred to any process which can operate automatically without occupying working memory capacity. This includes perception, attention, and language processes, as well as associative learning, habitual, and automated behavior patterns, which lead to many dual-process theories varying regarding application orientation. In the following the two systems will be described in more detail based on the established work of Kahneman and colleagues (Kahneman, 1973, 2003; Kahneman & Frederick, 2002, 2007; Tversky & Kahneman, 1971, 1974) as well as Epstein and colleagues (Epstein, 1994; Epstein, Lipson, Holstein, & Huh, 1992; Epstein & Pacini, 1999; Epstein, Pacini, Denes-Raj, & Heier, 1996). The first system is called system 1 (Kahneman, 2003) or intuitive-experiential system (Epstein, et al., 1996) and described as working fast, automatic, effortless, associative, implicit, and is associated with affect (Epstein, et al., 1996; Kahneman, 2003). In contrast, the second system is called system 2 (Kahneman, 2003) or analytical-rational system (Epstein, et al., 1996) and described as working slow, intentional, effortful, analytic, flexible, rule-governed and is more likely to be consciously monitored and deliberately controlled (Epstein, et al., 1996; Kahneman, 2003). Epstein (1994) postulated that the intuitive-experiential system involves general implicit beliefs or schemas which are derived from previous affective experiences and are not simply isolated constructs, but rather organized in an overall adaptive system. In contrast, the analytical-rational system is associated with conscious beliefs and is capable of high levels of abstraction and long-term delay of gratification. It is assumed that both systems normally work in integrated interaction, but that sometimes a conflict appears which is then experienced as a struggle between feelings and thoughts (e.g., Denes-Raj & Epstein, 1994). Moreover, Epstein and colleagues (1996) suggested that it depends on several individual or situational factors whether the intuitive-experiential or the analytical-rational system is dominant: Besides the situational properties of a situation (e.g., a mathematical problem is rather solved by the analytical-rational system), it depends on the individual preference of a person for relying on one system more than on the other. Additionally, it depends on the degree of affective involvement of a person and the degree to which a situation requests personal experiences.

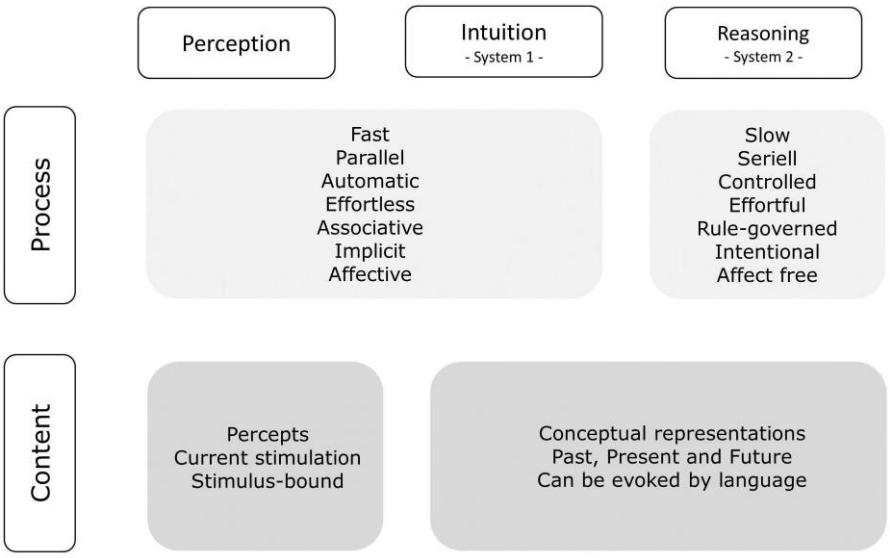

Figure 7 The processes and contents in the two information processing systems adapted from Kahneman (2003).

The approach of Kahneman (2003) concentrated in particular on judgments. He postulated that the operating features of system 1 are similar to perceptual processing (see Figure 7. However, it is not restricted to perception alone. He assumed that intuitive judgments (system 1), besides percepts deal with concepts and can be evoked by language. Together, percepts and intuitive operations generate impressions of objects of thoughts and perception. In contrast, system 2 is nearly involved in all judgments independently whether they are based on impressions or rational reasoning. The judgments associated with system 2 are always intentional and explicit. Moreover, Kahneman and Frederick (2002) suggested that even though system 2 monitors the processing of system 1, such monitoring is rather lax, allowing intuitive judgments to be expressed. Whether a judgment appears to be intuitive or corrected by system 2, depends on the accessibilities of competing considerations and the accessibility of metacognitive awareness of bias (Kahneman, 2003). In sum, there appear to be two separated but interacting processing systems, from which one is associated with intuitive, experiential, automatic, and effortless processes (from now on called system 1), while the other system is associated with rational, analytic, intentional and effortful processes (from now on called system 2).

However, the question remains how to investigate which processing mode is used for which operation or task. Kahneman (2003) suggested that the effect of the performance of two congruent tasks indicates best whether or not a given mental process belongs to system 1 or system 2: Assuming that the overall mental capacity is limited, concurrent tasks can only be performed simultaneously up to a certain limit. It depends on the demand of each task when the limit is achieved. He proposed that effortless, automatic tasks (i.e., relying on processes of system 1) do not suffer or cause interference when combined with concurrent tasks, while effortful tasks (i.e., relying on processes of system 2) are susceptible to interference (see also Kahneman, 1973). Over the years of research various theories of how subjects perform two tasks simultaneously, not necessarily related to dual-process theories were developed. Four further common approaches, differing in the assumptions if and how two tasks may be processed simultaneously will be presented. These approaches emphasize the importance of executive functions involved in dual-tasking processes. Figure 8 provides a graphical overview about the four approaches of dual tasking.

In the *capacity sharing* theories it is assumed that people share processing capacity or mental resources among tasks (Pashler, 1994). Therefore, performing more than one task at a time leads to less capacity for each single task, resulting in diminished performance. It can be distinguished between two theoretical approaches within these theories. On one hand there is the *single-resource /unitary-resource* approach, in which it is suggested that there is only one mental resource with limited capacity. The assumption of Kahneman (1973, 2003) that only effortless tasks can be processed in parallel, taps in such approach. On the other hand there is the *multiple-resource* approach (Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, Sandry, & Vidulich, 1983), in which it is postulated that there is more than one resource. It is assumed that interference between tasks occurs only, if the two tasks rely on the same resource. As long as they apply different resources two tasks can be performed simultaneously.

In contrast, in *bottleneck* theories it is suggested that some mechanisms are only dedicated to one task at a time. If two tasks require the same mechanism for the same period of time a bottleneck ensues, in which only one task can be processed, leading to a delay or impairment of the second task (Pashler, 1994). Pashler assumed that this corresponds not only to punctate tasks but also to continuous tasks, if both tasks need access to the bottleneck mechanism. There is a broad discussion about when the bottleneck occurs. Different theorists suggested diverse points in process when a bottleneck occurs (c.f. D. E. Meyer & Kieras, 1997a). Broadbent

(1958) for example assumed that a bottleneck exists at a perceptual level (*perceptual bottleneck*), at the point where stimuli are identified and their meanings are determined. On the contrary, various authors (Pashler, 1984; M. C. Smith, 1967; Welford, 1967) assumed that it is possible to identify multiple stimuli at a time. However, then this information is stored in short-term working memory, because the process of response-selection is only able to deal with one task at a time (*response-selection bottleneck*). Therefore, the response on the second task is delayed. In a further approach (a.o. postulated by Keele, 1973) it is assumed that the bottleneck does not appear until onset of the movement-production process (*movement-production bottleneck*). This means that this process is only able to prepare and initiate individual movements successively and therefore only one task at a time can be processed.

A third dual-tasking approach is the *crosstalk* model. In this model it is supposed that task interference occurs because of the same content the tasks share and not due to the kind of operation that has to be carried out (c.f. Pashler, 1994). Logan and Gordon (2001) proposed that one task interferes with a second task when the task set of the second task is also relevant for the first task (or the other way around). For example, in a study by Navon and Miller (1987) words were presented in different locations belonging either to the category city names or to the category boys' names. Depending on the locations participants were asked to indicate whether the presented word is a boys' name ("yes" or "no"), while they had to indicate whether the word presented in another locations is a city name ("yes" or "no") simultaneously. The authors found that when in task two (city names) the distractor words were boys' names the reaction time increases in the parallel first task (boys' name). Those findings support the assumption that when two tasks share the same task set between-tasks crosstalk occurs. This interference does not occur when both tasks have independent contents (Logan & Gordon, 2001).

In the last approach presented here, the aforementioned three theories and models are integrated into one approach. In the *executive-process interactive control (EPIC)* architecture (D. E. Meyer & Kieras, 1997a, 1997b) it is assumed that under certain conditions the response-selection processes for two simultaneous tasks overlap at a procedural cognitive level and therefore, two tasks can be performed simultaneously without severe impairments. However, further contextual factors could lead to a preclusion of this overlap of response-selection processes, resulting in a delay of the secondary task. For example, when participants have to move their eyes in opposite directions for each task this would not lead to a response-selective overlap between the two tasks and therefore, does not lead to a delay in one of the tasks. The crucial point of this theory is that D. E. Meyer and Kieras did not assume a central bottleneck, but rather that executive processes, like strategy application, are flexible to manage task sequences at various levels according to task priority instructions. The authors assumed that selected task responses are either stored in working memory or are sent to the motor processes leading to a direct reaction (D. E. Meyer & Kieras, 1997a).

Overall, there appear to be two separated but interacting processing modes. One is described as being slow, effortless, automatic, and affective charged (system 1), the other as effortful, intended, analytical, and affect free (system 2). According to Kahneman (1973, 2003) it depends on the processing modes whether two tasks can be performed simultaneously. However, approaches describing how two tasks might be processed simultaneously (or not), differ across researchers. Still, it seems to be a general agreement that there has to be an executive mechanism managing the processing of two simultaneous tasks. The next section will discuss studies investigating the involvement of executive processes in dual tasking.

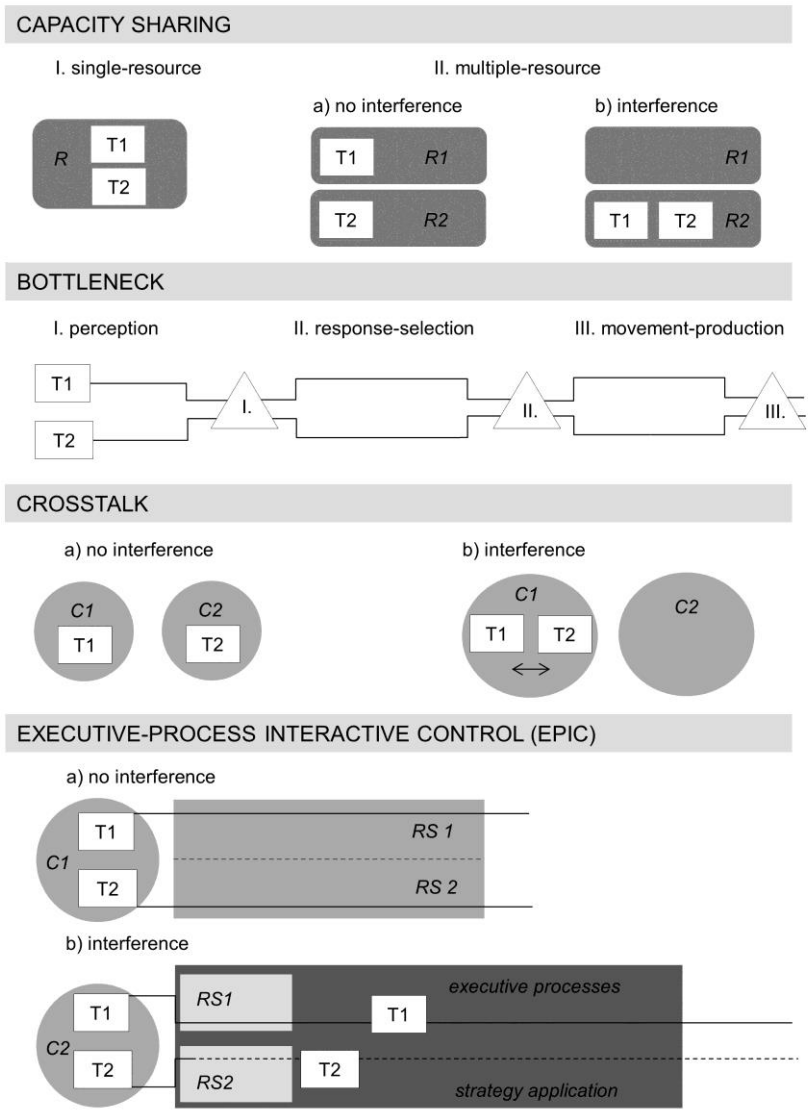

Figure 8 Graphic representation of the four different dual-tasking approaches described in the text.

The capacity sharing model postulates that tasks can be performed simultaneously until working to capacity. The bottleneck approach suggests that tasks can be performed simultaneously until a bottleneck appears. Depending on theory it appears either at perceptual level, at response-selection or movement-production. In the crosstalk theory it is assumed that interference occurs when two task share the same content. The executive-process interactive control architecture integrates the former approaches and suggests simultaneous performance of two tasks as long as the context allows a response-selection overlap. If no overlap occurs executive processes have to apply strategies in order to manage the sequence of the tasks. R = resource, T = task, C = content, RS = response-selection.

3.4.1.2 Dual tasking and the role of executive functions

Regardless of the various theoretical approaches, it becomes obvious that there has to be a mechanism that organizes the order of the tasks when they cannot be processed simultaneously. D. E. Meyer and Kieras (1997a, 1997b) suggested a supervisory function of being involved and got support from other studies demonstrating the inclusion of executive functions in the dual-tasking process (Cooper, Wutke, & Davelaar, 2012; De Jong, 1995). In his study De Jong (1995) investigated how the performance of two parallel tasks is organized and controlled. Participants had to perform two different tasks in parallel: an auditive task, in which participants were asked to indicate whether the current tone is high or low and a visual task, in which they were asked to indicate whether the current figure is a square or a diamond. Across the three experiments the tasks differed in following parameters: the time participants had to initially prepare for the first tasks (*stimulus onset asynchrony* between 100 and 800 ms), the time to prepare for a switch between tasks (*inter trial interval* between 500 and 2,000 ms),

and the information which task has to be performed next (unexpected vs. expected order, and presented cues before each trial informing about the next tasks). The results of this study suggested that performance of simultaneous tasks as well as the switch between these tasks is prepared in advance. For this, he proposed similar to D. E. Meyer and Kieras (1997a, 1997b), that a "superordinate control structure" (De Jong, 1995, p. 22) is involved that procures in which order the central processing mechanism (also called central executive, c.f. section 3.2) processes these tasks and initiates a switch between them.

Cooper and colleagues (2012) investigated this central processing mechanism (i.e., the central executive) in more detail. They conducted a study in order to get increased insight on the interactions and roles of executive control functions. Executive control functions are understood as processes which organize the processing of two tasks. That means these functions implement set shifting or protect an ongoing task from disruption while still be flexible to execute the second task (monitoring/updating) (c.f. Cooper, et al., 2012; Monsell, 2003). Cooper and colleagues (2012) used the dual-tasking approach to segment the central executive and thereby testing for the diversity of executive functions (based on results from Baddeley, 1998a; Miyake, et al., 2000; see also section 3.2 for a detailed discussion about the central executive and a possible segmentation of this function). In the experiments participants had to perform either the random letter generation task as primary task (in which they were asked to generate a random sequence of 100 letters (A-J) by selecting letters with the mouse on a screen) or the WCST (for a description of this task see sections 5.3.2.3 and 6.3.2.2). Simultaneously, participants had to perform each of the following three secondary tasks: go/no-go task (participants were asked to react to either a single beep or a double beep while inhibiting the reaction to the other), 2-back task (participants heard a sequence of numbers and had to answer vocally with "yes" when a current number was mentioned two trials before), and digit switching task (participants heard a sequence of numbers and had to respond vocally for four times whether the current number is higher or lower than the number 5, the next four times they were asked to tell whether the current number is odd or even etc.). Cooper and colleagues found that the interference profiles across the different dual tasks do not support the assumption of a single-resource model of cognitive processing. Instead, the profiles are consistent with a segmentation of the central executive (see section 3.2 for detailed information about executive subfunctions). Moreover, the authors argued that the central processing (i.e., central executive) is not completely parallel, but is itself dependent to bottlenecks associated with set-shifting and memory monitoring/updating.

The importance of executive functions in dual tasking was additionally supported by studies investigating patients with executive dysfunctions for example patients with Parkinson disease (Dalrymple-Alford, Kalders, Jones, & Watson, 1994), Alzheimer disease (Greene, Hodges, & Baddeley, 1995; Logie, Cocchini, Delia Sala, & Baddeley, 2004), schizotypal personality disorder (Harvey, Reichenberg, Romero, Granholm, & Siever, 2006), and patients with dysexecutive syndrome (Baddeley, Della Sala, Papagno, & Spinnler, 1997). Those patients showed inferior performance in dual tasking compared with healthy control participants. Further support for the involvement of executive functions in dual tasking comes from studies using task-switching paradigms in order to investigate whether there is a central executive or a segmentation of various executive control processes. The next section will give an overview about such studies.

3.4.1.2.1 Task switching

In the field of task-switching research, different paradigms were emerged over the years, all in order to investigate flexible task performance and the involved executive control processes. Here, only a short overview

about such paradigms will be presented, for more detailed reviews see for example Kiesel et al. (2010) or Monsell (2003).

One of the first attempts was made by investigating *mixed-task blocks* vs. *single-tasks blocks* (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Spector & Biederman, 1976). In mixed-blocks participants had to switch between task A and B in each trial (ABAB). In contrast, in single blocks participants had at first to perform task A and in a second block task B (AAA vs. BBB). Comparing the performance in mixed-task blocks with the performance in single-task blocks revealed a higher reaction time for switches between two different tasks than for repetition trials (called switch costs see e.g., Allport, et al., 1994; Jersild, 1927; Spector & Biederman, 1976). However, Roger and Monsell (1995) argued that this between-block comparison could be influenced by confounding factors for example, different effort or arousal. Moreover, they assumed that mixed-task blocks require abilities that are not required in single-task blocks for example, "keep two rather than one task set 'active' or available" (Rogers & Monsell, 1995, p. 210). Therefore, the authors developed a new paradigm: *predictable task switching*. In this paradigm the order of the tasks is known by the participants and changes every *n* trials (AABBAA or AAAABBBBAAAA). In this paradigm the mentioned confounding factors should be diminished. Studies using this paradigm supported the finding that again switch costs appeared (Monsell, Sumner, & Waters, 2003; Rogers & Monsell, 1995). In order to avoid the predictability of task sequences a few other paradigms were developed: In the *task-cuing design* the order of task switches and repetition is random. Participants get to know which task has to be performed next, by receiving an explicit task cue right before each upcoming trial or accompanying the target stimulus (see e.g., Meiran, 1996; Sudevan & Taylor, 1987). In the *intermittent instructions* paradigm a sequence of trials involving task A has to be performed. From time to time a cue occurs that informs the participants about the action for the upcoming trial sequence. That could involve a switch to task B, but also to stay at task A (e.g., Altmann & Gray, 2008; Gopher, Armony, & Greenshpan, 2000). A somewhat different approach is the *voluntary task selection* (e.g., Arrington & Logan, 2004; Liefooghe, Demanet, & Vandierendonck, 2010). Hereby, participants can decide for themselves when to switch to the other task. Their only information is that they have to perform all tasks randomly but balanced. In all mentioned studies using an unpredictable paradigm, reaction time for switching trials was again higher than for repetition trials, indicating switch costs.

As mentioned above task-switching paradigms were often used to investigate executive control processes (c.f. Arrington & Logan, 2004; Jersild, 1927; Kiesel, et al., 2010). Independently of the task-switching paradigm, various studies found a direct relationship to several executive control processes (e.g., Arbuthnott & Frank, 2000; Aron, Monsell, Sahakian, & Robbins, 2004; Arrington & Yates, 2009; Butler, Arrington, & Weywadt, 2011; Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999). For example, Arbuthnott and Frank (2000) showed in a task-cuing paradigm that especially task-set inhibition is a crucial executive control process. Additionally, Aron and colleagues (2004) demonstrated the important role of inhibition of task sets but also the involvement of top-down control of task sets (i.e., subject-initiated/endogenous control that directs the attention to a particular attribute of the task set or selects a stimulus-response rule) in an intermittent instruction paradigm. Using a voluntary task selection paradigm Butler and colleagues (2010) revealed that task-switching performance was related to working memory capacity. The tasks used in these studies were mostly the well-established switching tasks, consisting of numbers (in which participants were asked to indicate whether the current number is odd or even or higher/lower than the number five) or letters (in which participants would have to indicate whether the current letter is a vowel or a consonant). These studies reveal an involvement of various executive control processes supporting again the assumption of a segmentation of the central executive

(see section 3.2). In line with these findings is a study by Mecklinger and colleagues (1999), demonstrating the involvement of different executive control processes. They investigated patients with left and right brain damage, performing an object (round vs. not round) vs. spatial (which object is further away from the middle: upper vs. lower object) switching task. The authors found that the patient groups had different executive problems: While the patients with left brain damage demonstrated problems with the reconfiguration of task sets (i.e., internally guided actions), patients with damage to the right side of the brain had problems with the suppression of the inappropriate task set (i.e., externally guided action like stimulus-response actions). Therefore, Mecklinger and colleagues assumed differentially functional executive (control) functions to be involved in task-switching paradigms, instead of one functional executive process.

Taken together, dual-tasking as well as task-switching approaches have demonstrated that the simultaneous performance of two tasks involves several executive control processes for instance, set-shifting and monitoring/updating. Hereby, the approaches support the assumption of a segmentation of executive processes rather than the assumption of a central executive (c.f. section 3.2). Compared with dual-tasking approaches, task-switching paradigms concentrate in particular on the switch between the two tasks and the associated switch costs. Even though some dual-tasking studies used also simple task-switching paradigms (e.g., De Jong, 1995) most of the studies are interested in the simultaneous performance of more complex tasks and relationships than research with task-switching paradigms does (see section 3.4.1.2). The question remains whether brain areas involved in dual-tasking and task-switching paradigms may be different or whether they require similar brain regions. The following section addresses this question and reports studies investigating associated brain regions.

3.4.1.3 Neural correlates of dual tasking and task switching

The findings concerning neural correlates associated with dual-tasking or task-switching paradigms are heterogeneous. At first studies investigating the neural correlates underlying dual-task performance will be addressed followed by those investigating in particular task-switching performance. In the end the results of one study comparing underlying neural correlates of dual-tasking and task-switching performance will be presented.

Some studies using fMRI (for details about fMRI see section 4.3.4) found activation in certain brain areas associated with performance in a dual-tasking paradigm (D'Esposito et al., 1995; Deprez et al., 2013; Dreher & Grafman, 2003; Dux, Ivanoff, Asplund, & Marois, 2006; MacDonald III, Cohen, Stenger, & Carter, 2000; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006; Szameitat, Schubert, Müller, & von Cramon, 2002; Wu, et al., 2013). Most activation patterns were found in prefrontal areas, for example, in parts of the lateral PFC (Dux, et al., 2006; Szameitat, et al., 2006), or in particular the dlPFC (D'Esposito, et al., 1995; MacDonald III, et al., 2000; Schubert & Szameitat, 2003; Szameitat, et al., 2002), and the ACC (D'Esposito, et al., 1995; MacDonald III, et al., 2000). These brain areas are associated with executive control functions and were mostly interpreted to be involved in the coordination of two interfering tasks. However, some studies found also activations in parietal areas, such as the superior parietal cortex (Szameitat, et al., 2002; Wu, et al., 2013) and in different parts of the cerebellum (Wu, et al., 2013). A recent study found a right-sided fronto-parietal network and the cerebellum to be activated when comparing a dual-task paradigm with each of its single tasks (Deprez, et al., 2013). In contrast, other studies found no specific brain areas associated with the performance of a dual-tasking paradigm, but an increase in activation in brain areas involved in each component task (Adcock, Constable, Gore, & Goldman-Rakic, 2000; Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; Erickson et al., 2005; Klingberg, 1998, 2000). The increase in activation was mostly associated with the

involvement of additional executive processes that are necessary to solve the dual-tasking problem. Nonetheless, there are also studies demonstrating a decrease in brain activation associated with dual-tasking performance, for example in the dlPFC (Jaeggi et al., 2003), parietal and temporal brain areas (Just et al., 2001), as well as somatosensory brain areas (Gazes et al., 2010). The decrease in activations was mostly associated with the limited resources available for each component task. Overall, the findings of these studies point in the direction that the decrease in activation is associated with brain areas specific for each component task, while the increase in activation concerns a cortico-subcortical circuit associated with executive functions (Heyder, Suchan, & Daum, 2004). In this context another possible explanation for the heterogeneous findings should also be considered. In the review by Szameitat, Schubert and Müller (2011) various studies were analyzed in order to investigate the underlying neural correlates of dual tasking. The authors found that the different studies not only used different paradigms that could lead to different activation patterns, but also differed in their imaging analyses leading to different activation patterns. Therefore, the results are not directly comparable. Szameitat and colleagues suggested that future studies should use at least the same imaging analyses in order to be compared and thus, getting a better overview about the brain areas that might be involved.

FMRI-studies investigating neural activations during task-switching paradigms found also prefrontal and parietal areas to be involved, regardless of the task-switching paradigm used (Brass, Ullsperger, Knoesche, von Cramon, & Phillips, 2005; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Forstmann, Brass, Koch, & von Cramon, 2006; Forstmann, Ridderinkhof, Kaiser, & Bledowski, 2007; Hyafil, Summerfield, & Koechlin, 2009; Mueller, Brass, Waszak, & Prinz, 2007; Soon, Brass, Heinze, & Haynes, 2008; Wylie, Javitt, & Foxe, 2003). Noteworthy are the findings of studies investigating voluntary task switching. They found consistently the rostral cingulate zone (RCZ) to be activated (Forstmann, et al., 2006; Forstmann, et al., 2007; Mueller, et al., 2007). Mueller and colleagues (2007) demonstrated that this zone is involved in internally guided actions (voluntary selection) compared with externally guided actions. Some studies used EEG in order to investigate the temporal resolution of the activation pattern of prefrontal and parietal regions (Brass, et al., 2005; Forstmann, et al., 2007; Wylie, et al., 2003). However, the results are heterogeneous which could be due to the different points of interests of the studies: For example, Brass and colleagues (2005) focused on whether prefrontal and parietal areas are involved in different functions of cognitive control. The authors found the involvement of the PFC in updating of general tasks-settings, which biases the following stimulus-response associations in the parietal cortex. In contrast, Forstmann and colleagues (2007) were interested in the neural bases of agency-related processes and their temporal dynamics (choice vs. non-choice conditions). They found an early parietal activation (parieto-occipital) interpreted as a categorization process for the choice condition compared with the no-choice condition. This activation was followed by a frontal activity, associated with the voluntary selection of tasks sets. Finally, Wylie and colleagues (2003) addressed the question of how switch costs derive: Whether switch costs derive because before a new stimulus is presented participants need time to disengage from task A to prepare for the upcoming task B (reconfiguration theories) or because after a stimulus is presented participants need time to disengage from the goal of task A to adapt to the goal of task B (competition theories). Hereby, Wylie and colleagues (2003) assumed, based on previous research, that frontal areas are associated with reconfiguration processes while parietal areas are associated with the competition processes (for a detailed information see Wylie, et al., 2003). Therefore, if the switch costs are due to the reconfiguration process the frontal areas should be activated before the parietal areas. However, the authors found previous activation of the parietal areas than frontal areas. Consequently, they interpreted their findings in accordance with the competition hypothesis.

So far, only one study compared the neural activation during a task-switching paradigm with the neural activation during a dual-tasking paradigm (Dreher & Grafman, 2003). In the task-switching condition participants had either to perform task 1 (vowel or consonant) or task 2 (upper or lower case) indicated by the color of the letter (red = task 1; green = task 2). In the dual-tasking condition participants had to perform both tasks simultaneously: In order to indicate whether the letter was a consonant or in lower case they were asked to push the left button and the right button otherwise. The fMRI results revealed that both paradigms (dual tasking and task switching) activated a common prefrontal-parietal neural network when compared with a baseline task. Dreher and Grafman (2003) suggested that the activated network is neither specific for task-switching paradigms nor for dual-tasking paradigms but rather for more generally executive processes. Nevertheless, comparing the neural activation between the dual-task and the task-switching paradigm, revealed more activity in the RCZ during the dual-task paradigm, and more activation in the lateral PFC, as well as the bilateral inferior parietal sulcus during the task-switching paradigm.

Overall, the findings concerning the neural correlates associated with dual-tasking paradigms and task-switching paradigms are heterogeneous. However, most of the findings suggest the involvement of prefrontal and parietal areas, which are associated with a network of executive functions in dual-tasking and task-switching paradigms. As can be seen by results of task-switching studies, the temporal resolution of the involved areas depends on the focus of the study. Regarding studies addressing explicitly dual tasking it is still unclear whether or not dual tasking involves certain brain areas or whether it just leads to an increase/decrease in activity in the brain areas involved in the component tasks or not. Nonetheless, the neuroimaging studies support the assumption of the behavioral and patient studies demonstrating the important role of executive functions in dual-tasking and task-switching paradigms. Due to this fact dual-tasking paradigms are also used in the decision-making field in order to investigate the role of executive functions or the underlying information processing system in more detail. Therefore, the following section gives an overview about studies using dual-tasking paradigms to investigate decision making under ambiguity and risk in more detail.

3.4.1.4 Dual tasking in the field of decision making

As mentioned at the beginning of section 3.4.1, dual tasking becomes also a topic of interest in the field of decision making. Here, it is of special interest to investigate the underlying processing systems (see section 3.4.1.1 for more details). For this purpose the decision-making tasks display the primary tasks while simultaneously a secondary task has to be performed. So far, only two studies investigated dual tasking in decisions under ambiguity (Hinson, et al., 2002; Turnbull, Evans, Bunce, Carzolio, & O'Connor, 2005) and two studies in decisions under risk (Starcke, et al., 2011; Whitney, Rinehart, & Hinson, 2008), all in healthy participants. In the following the results of those studies will shortly be presented.

3.4.1.4.1 Decisions under ambiguity in situations with additional cognitive demand

Turnbull and colleagues (2005) used a dual-tasking paradigm in order to investigate the underlying information processing system of the IGT (see Table 1 for a brief description of this task). Different studies using the IGT suggested that to perform well on this task participants have to rely on their intuition as well as on their experiences from previous trials instead of their cognitions (Bechara, Damasio, & Damasio, 2000; Bechara, et al., 1997; Dunn, et al., 2006; for detailed information see section 3.1. and 3.2). Therefore, Turnbull and colleagues (2005) assumed that affective-based learning is more important to perform decisions under ambiguity than cognitive reasoning. Based on the approach of Kahneman (1973, 2003, see also section 3.4.1.1), they

assumed that the IGT would tap into system 1. Consequently, the performance of a secondary executive task in parallel to the IGT should not interfere with the decision-making performance, because both tasks require different processing systems (see section 3.4.1.1 for more detail). In order to test this hypothesis Turnbull and colleagues conducted a study with three different groups: In the first group participants had to perform the IGT in parallel with an executive secondary task. The second group had to perform the IGT in parallel with a non-executive secondary task and the third group performed only the IGT. In the executive secondary task participants were asked to randomly generate numbers between 1 and 9 without using any sequences and patterns. This task was known to load on the executive system (Baddeley & Della Sala, 1996). In the non-executive task participants were asked to recite the number sequence 1 through to 9. This task was known to load on the phonological loop of working memory (Baddeley & Della Sala, 1996). The results supported the hypothesis by demonstrating that the IGT-performance between groups did not differ. Instead, all three groups showed the common learning curve over the 100 trials of the IGT.

Contrasting findings revealed a study by Hinson and colleagues (2002). The authors found that the performance in the IGT diminished when simultaneously a secondary task with working memory load had to be performed (for a detailed description of the study see section 3.2.2.1). Moreover, they measured SCRs and showed that during the working memory task no affective biasing signals were developed. Hinson and colleagues concluded that the lack of these signals lead to disadvantageous choices in the IGT. However, one reason for the contrasting findings could be that Hinson and colleagues used a modified version of the IGT. In this version overall payoffs were changed into less extreme ones, making it more difficult to identify the advantageous options. Additionally, the authors implemented an intermediated option between the advantageous decisions (small short-term gains but also long-term gains) and disadvantageous options (large short-term gains but long-term losses). This option offered long-term gains rather than long-term losses but of smaller magnitude than those of the advantageous options. Due to the fact that this task was changed in order to be more difficult, this could lead at the same time to higher involvement of working memory compared to the original version of the IGT and could consequently lead to interference between the secondary task and the decision-making performance.

Overall, these studies seem to be contrasting, while Turnbull and colleagues (2005) did not find interference between an executive task and decisions under ambiguity, Hinson and colleagues (2002) did. However, this discrepancy might be explained as followed: Decisions under ambiguity tap into system 1, when operationalized with the original version of the IGT. However, once the decision-making situation under ambiguity is a little bit more demanding (see the version of the IGT by Hinson, et al., 2002), system 2 seems to be additionally involved in the processing of information. This might indicate, the suggested controlling role of system 2 (c.f. Kahneman, 2003 and section 3.4.1.1). The following section will describe dual tasking in the context of decisions under risk.

3.4.1.4.2 Decisions under risk in situations with additional cognitive demand

While the findings in the field of decision making under ambiguity seem to be contrasting, the studies in the field of decision making under risk point both in the same direction: Additional cognitive load interferes with decision making under risk. Based on the study by Turnbull and colleagues (2005), a recent study used the GDT (for a brief description of this task see Table 1) and a secondary executive working memory task (n-back) in order to investigate the underlying information processes of decision making under risk (Starcke, et al., 2011). In the n-back task participants had to indicate whether or not the current number on the screen was the same

number as the number two trials (or one trial) before. Starcke and colleagues (2011) assumed that due to the fact that various studies demonstrated the involvement of executive functions in the GDT (Brand, Recknor, et al., 2007; Schiebener, et al., 2011; for detailed discussion see section 3.2.2.2) additional executive load should diminish the decision-making performance. The authors conducted a study with three different conditions: GDT plus 2-back task, GDT plus 1-back task, and GDT solely. The results showed that participants performing the 2-back task (high executive load) simultaneously to the GDT chose the disadvantageous options more often compared with participants performing the GDT solely. The difference between the groups performing the 1-back task (low executive load) and the GDT simultaneously as well as the GDT solely failed to reach significance. In accordance with the dual-process theory of Kahneman (see section 3.4.1.1) Starcke and colleagues (2011) assumed that both tasks (GDT and 2-back) tap into system 2 and thus the secondary task interferes with the primary task.

Similar results provided a study by Whitney and colleagues (2008). The authors used an explicit but instable decision-making task, in which participants had to play for a certain amount of money. In this task participants were able to choose between different explicit options: a certain gain option, a certain loss option, or a gambling option in which they could either win a high amount of money or lose it. However, the gains and losses differed in the amount of money as well as in the way they were displayed: either the winning or the losing probability was given. In the dual-tasking condition participants were asked to perform a working memory task in parallel. They had to remember a sequence of five consonants throughout a decision trial. After a decision was made participants were asked to indicate which letter was for example, at the third place. In the no-load condition, participants saw the letter sequence after each decision trial. The results demonstrated that in the dual-task condition participants made fewer decisions to gamble. Whitney and colleagues assumed that this is because of minimized cognitive effort due to limited cognitive resources: Gambling requires cognitive capacity in order to ponder/analyze the possibility to win/lose, which is not required in situations of a certain gain or loss.

Overall, the studies support the assumptions that decision making under risk taps into a different processing system than decisions under ambiguity namely system 2. The studies demonstrate that performing another task in parallel to risky decision making leads to disadvantageous decisions. This may be in line with the unitary-resource approach of Kahneman (1973, 2003; see also section 3.4.1.1 and Figure 8): Performing two effortful tasks, which therefore require system 2 rather than system 1 processes, leads to interference between these tasks and therefore to reduced task performance. The question remains, which underlying (executive) functions might be involved in performing a decision-making task and an additional task simultaneously. The third study of the current thesis (see chapter 6) investigated the underlying executive mechanisms of performing a risky decision-making task (GDT) simultaneously with an additional executive task (2-back task). Moreover, besides cognitive processes, affective processes are also involved in decision making (see section 3.1). Thus, the next chapter will address the issue of what happens when the affective route is additionally loaded, by giving an overview about affective influences and stress and their effect on decision-making performance.

3.4.2 Affective influences

The field of research regarding the influences of affect on cognitive processes in general is huge (for an overview see e.g., Dolan, 2002; Dolcos, et al., 2011; Pessoa, 2008, 2009). It reaches from studies investigating the influence of neurotransmitter associated with affective processing on cognitive processes (Harrison et al., 2004; Matrenza et al., 2004; R. L. C. Mitchell & Phillips, 2007), to studies investigating performance of cognitive processes in patients suffering from impaired affective processing, for example, depression (Levens & Gotlib, 2010), anxiety (Miu, et al., 2008), and mania (Adida et al., 2008). However, the focus of this chapter is on healthy participants and studies investigating the induction of affective states and their influence on decision making. Chapter 3.1 discussed the underlying affective processes of decision making and showed that when making decisions under ambiguity such processes are particularly involved in the guidance of a decision. However, when making decisions under risk these processes are more involved in the evaluation of a certain decision strategy. Moreover, several brain areas that are activated during the decision-making process are also associated with affective processing in general (c.f. sections 3.1.1 and 3.3). This suggests that various affective states may influence human decision making. For example, an angry person might take the risk to speed on the highway despite the speed limit and the possibility of getting caught by the police, while a relaxed person might be more likely to follow the speed limit. Before discussing studies investigating affective influences on decision-making behavior, the next section will at first give an overview about possibilities to induce affective states in the laboratory.

3.4.2.1 Laboratory induction of affect

There are various ways to induce affective states in participants in the laboratory. One option is the injection of adrenaline or the donation of psychotropic drugs, to increase persons' arousal (Schachter & Singer, 1962). Another possibility to induce affect is to transfer the arousal from one situation (e.g., increased arousal due to a training session on an ergometer) to a subsequent situation where the participant has to perform the task of interest (Zillmann, 1978). However, both induction methods are only possible when the participants are unaware to the impact of the medication they are taking (Reisenzein & Gattinger, 1982) or the cause of the arousal in the second induction method (Zillmann, 1978). Ekman (1982) let participants imitate the affective states (i.e., characteristic expressions of the affect) he wanted to induce. He showed that this imitation had influence on the heart rate and skin conduction of the participants (Ekman, 1993). Example for induction methods inducing affective states by modulating the cognitive contents of participants are the Velten mood induction procedure (Velten Jr, 1968) or the imagination of a self-experienced affective situation (positive or negative). The Velten mood induction procedure includes statements which describe either a positive or negative self-evaluation (e.g., "I have too many bad things in my life") or a somatic state (e.g., "Every now and then I feel so tired and gloomy that I'd rather sit than doing anything") (c.f. Velten Jr, 1968). Participants are instructed to feel the affect described. Such cognitive affect induction procedures are commonly used in current studies alongside the use of situational affective stimuli, for instance a film, a story, music, odors or other affect-laden, visual or auditive stimuli (c.f. Sokolowski, 2008; Westermann, Spies, Stahl, & Hesse, 1996). Usually these stimuli are presented in three different valences, positive, negative, and neutral, to induce different affective states across groups. One popular affective stimuli system is the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert). This system provides ratings of affect for a large set of affect evoking color photographs which are

internationally accessible and include across a wide range of semantic categories (c.f. Lang, et al., 2008). In the IAPS, over 1,000 pictures are listed regarding the three dimensions they were rated for: arousal, valence, and dominance/control. This simplifies the selection of standardized stimuli inducing the required affect.

To measure whether the affect induction was successful or not, it is possible to apply the facial action coding system (Ekman, 1978), in which small parts of the face are observed and expression changes regarding occurrence, duration and, ending of these changes are strictly protocolled. Thereafter, an experienced rater analyzes and compares this expression changes with common patterns for the affect which was intended to be induced. However, such procedure is rather elaborate. Therefore, self-report questionnaires listing adjectives with various response dimensions (e.g., Likert scale or visual analogue scale) are frequently used. Common questionnaires are the Positive Negative Affect Scale (PANAS; Watson & Clark, 1999) or the language free Self-Assessment-Manikin (Lang, 1980) containing manikins illustrating different degrees of valence, arousal and dominance. Sometimes also heart rates, blood pressure, and skin conductance are measured (Sokolowski, 2008). However, these measurements only prove that the participants are aroused, but give no information about the valence of the affect.

Overall, this section summarized the most common affect induction procedures. For detailed information about various induction methods and the effectiveness and validity of such measures please be referred to (Westermann, et al., 1996). In the following section studies will be discussed investigating the influence of several affective states on decision-making performance.

3.4.2.2 Affective influences on decision making

The fact that affect influences certain cognitive processes which are associated with decision-making processes, was shown by Bless and Schwarz (1999) and Clore, Schwarz and Conway (1994). These studies demonstrated that negative affect in particular increases the probability for people to rely on deliberative processes and systematic elaboration. Based on these studies De Vries and colleagues assumed that affective states also influence the usage of decision strategies (De Vries, Holland, & Witteman, 2008a): While negative affect appears to be compatible with thoughtful, deliberative decision strategies (Bless & Schwarz, 1999; Clore, et al., 1994), De Vries and colleagues (2008a) suggested compatibility between positive affect and intuitive decision strategies. They specifically aimed to investigate whether a fit or a non-fit, respectively, influences the subjective value of a decision outcome. Therefore, following experimental design was conducted: In order to induce affective states participants saw either a sad or happy video clip. The core part was the question which of two presented Thermos flasks the participants would like to win in a lottery. Participants were asked to decide either intuitively or deliberatively (i.e., they had to think about the pros and cons) which Thermos flask they preferred. De Vries and colleagues found that a fit between affective state and decision strategy improves people's subjective value of their decision outcome (De Vries, et al., 2008a): Participants who saw a sad video and were able to deliberate the pros and cons before making a decision, as well as participants who saw a happy video and had to make their decision based on their feelings, valued the outcome of their decision more than participants who had no fit between affective state and strategy use (i.e., participants who saw the happy video and needed to deliberate about their decisions, and participants who saw the sad video and needed to make their decision based on their feelings). Based on these findings it is not farfetched to suggest that affective states may influence decisions differentially under risk and ambiguity. Decisions under ambiguity are best done by relying

on their intuition and feelings (Bechara, et al., 1997, see also chapter 3.1.2.1), while in decisions under risk participants decide more advantageously when they apply more deliberative strategies (Brand, Heinze, et al., 2008, see also section 3.2.2.2). The following sections will give further insight to this matter by summarizing studies that investigated the influence of affective states on decision making under ambiguity (section 3.4.2.2.1) and risk (section 3.4.2.2.2).

3.4.2.2.1 Decision making under ambiguity in affective situations

Based on their findings that positive affective states fits affect-based (i.e., intuitive) decision-making strategies (De Vries, et al., 2008a, see also section 3.4.2.2), De Vries and colleagues investigated the possible influence of affective states on the IGT (De Vries, Holland, & Witteman, 2008b; see Table 1 for a description of the task). The authors hypothesized that positive affect should enhance advantageous decision making in the IGT. Specifically, they assumed that it should enhance the performance in the second block of the IGT (trials 20-40, pre-hunch phase; Bechara, et al., 1997), in which participants develop a preference for the good decks of the task without explicitly knowing the reason for this preference. De Vries and colleagues (2008b) argued that because in this phase of the IGT participants start to develop affective signals (somatic markers) associated with the different blocks, participants in a positive affective state rely more on their feelings and consequently show enhanced IGT performance. In contrast, participants in a negative affective state should rely less on their feelings and thus show less good decision-making performance in the second block. The results supported their assumption. While experiment one demonstrated significant correlation between affect and IGT performance in the second block only, experiment two and three revealed that participants in a positive affective state, induced by a positive film clip, selected cards from deck C and D (good decks) more often, compared with participants in a negative affective state (induces by a sad film clip). Moreover, experiment three also showed that in the last block of the IGT (trials 81-100, conceptual period; Bechara, et al., 1997) participants, who saw the sad film before performing the task, chose the good decks more often than the bad decks compared with participants in a positive affective state. However, De Vries and colleagues reported that further analysis revealed that affect only influences the second block of the IGT. At this point results of this study need to be looked at carefully, because especially regarding the performed additional analysis, the methodological procedure remains incomprehensible. Therefore, the conclusion that only the second block is influenced by induced affect can only be made with caution. Particularly, because the finding that in the last block of the IGT participants with a negative affective state performed superior than participants with a positive affective state is in accordance with other research findings: This period is known to be more associated with deliberative decision making (Bechara, et al., 1997; Brand, Recknor, et al., 2007; Maia & McClelland, 2004), which in turn is more favored in a sad affective state than in a positive affective state (De Vries, et al., 2008a). In sum, the study revealed that compared to a negative affective state, a positive affective stat is associated with superior performance in the pre-hunch phase of the IGT. However, conclusions about the affective influence on other phases of the IGT, in particular the conceptual phase, appear to be less clear.

Another study demonstrated that whether decision making is influenced by affective processing depends on an affective regulation mechanism (Heilman, Crişan, Houser, Miclea, & Miu, 2010). In this study participants watched short video clips (of negative value to induce a negative affective state) before performing the IGT. The participants were divided into three groups. The first group was instructed to cognitive reappraise

their affective states during the video to decrease the negative affect. That means, "to think about what they were seeing in such a way that they did not feel anything at all" (Gross, 2002, p. 284). The second group was instructed to apply expressive suppression (i.e., hiding the affective reactions; Gross, 2002) as an affect-regulation strategy. The third group served as control group and did not receive any instruction. After watching the video clip participants were asked to fulfill the PANAS. This was done in order to analyze whether or not the film clip induced the required affective state. Results confirmed that the induction was successful. Moreover, it was found that participants of the "cognitive reappraisal" group demonstrated better decision-making performance in the transition between pre-hunch and hunch phase of the IGT compared to participants of the control group. Furthermore, participants who applied expressive suppression as an affect-regulation strategy, showed comparable IGT performance than participants of the control group. Heilman and colleagues (2010) assumed that negative affect increases physiological noise, which inhibits the somatic markers and consequently leads to disadvantageous decision making. A similar assumption was made by Preston, Stansfield, and Bechara (2007) see section 3.4.3.3.1. Hence, when people engaged in cognitive reappraisal the physiological noise decreased, thus explaining the better decision-making performance in reappraisers. In contrast, engaging in expressive suppression increases sympathetic activations (Gross, 1998) that potentially interfere with somatic markers. This may explain disadvantageous decision making in subjects applying expressive suppression as affective regulation. Even though affect was induced artificially in the mentioned studies, the naturally occurring differences in affective states as measured with the PANAS support those findings. Participants who indicated to be in a negative affective state on the PANAS, without further laboratory affect induction, demonstrated inferior IGT performance (De Vries, et al., 2008b; Suhr & Tsanadis, 2007). However, when engaging in cognitive reappraisal the effect of the negative influence of natural occurred negative affect on decision making is reduced (see study 2 in Heilman, et al., 2010).

Overall, those studies have shown that it appears to depend on the value of the affective state whether it impairs or enhanced decision making in ambiguous situations: While positive affect leads to advantageous decisions, negative affect leads to disadvantageous decision. This is because negative affect seems to lead to sympathetic activation, which inhibits somatic markers that play a crucial role in decisions under ambiguity (Bechara, et al., 1996; Heilman, et al., 2010; Preston, et al., 2007). Moreover, subjects in a negative affective state apply more deliberative strategies known to be of little benefit for IGT task performance (De Vries, et al., 2008b). In contrast, subjects in a positive affective state rely more on their feelings, which is superior for decision making under ambiguity (e.g., Bechara, et al., 1999). However, the affective influence seems to interfere with the usage of affective regulation. Furthermore, there appears to be a differentiation between the decision-making phases in the IGT: The results pointed out that in particular in the pre-hunch phase and at the beginning of the hunch phase (second and third block of the IGT, during which participants need to rely on their gut feeling), positive affect seems to support superior decision making, while negative affect does not (De Vries, et al., 2008b; Heilman, et al., 2010). This was not shown for the other decision-making phases. In addition, preliminary findings indicate that in the conceptual phase (last block of the IGT, where the participants know the rules and contingencies of the task) negative affective states appear to be related with superior decision-making performance (De Vries, et al., 2008b). Due to the fact that the last phase of the IGT was found to be associated with deliberative decision making (Bechara, et al., 1997; Brand, Recknor, et al., 2007; Maia &

McClelland, 2004), it is assumable that negative affect has a comparable effect on decision making under risk. The following section will review studies examining the affective influence on decisions under risk.

3.4.2.2.2 Decisions under risk in affective situations

Besides the influence of affective state and the role of affective regulation in decisions under ambiguity Heilman and colleagues (2010) were additionally interested in their influences in decisions under risk. Using the BART (see Table 1 for a brief description of this task) as a measurement of decisions under risk the authors found that naturally occurring negative affect (experiment 2 of their study) led to higher risk aversion compared to positive affect. This finding is in accordance with studies demonstrating that negative affect leads to an enhanced engagement in deliberative strategies (Bless & Schwarz, 1999; Clore, et al., 1994), which in turn result in less choices of high-risk decisions (Brand, Heinze, et al., 2008). However, compared with participants who used expressive suppression or no affect-regulation strategy, the application of cognitive reappraisal as an affect-regulation strategy in a negative affective state, increased risk-seeking. The last effect was found in their first experiment, during which the negative affect was induced via a negative movie clip. Heilman and colleagues argued that the effective down regulation of the experienced negative affective state gives an increased sense of affective control which decreases risk aversion. This is in line with other previous findings that the feeling of control mediates the relation between affect and risk taking (Lerner & Keltner, 2001).

The study by Cassotti and colleagues (2012) highlighted the affective influence on decision making under risk from a slightly different angle. It is well known that participants decide differently according to how the options are offered in a decision-making situation (framing effect; Kahneman, 2003; Kahneman & Frederick, 2007; Reyna, 2004): If options are offered in terms of a certain gain, subjects prefer the risk averse choice (i.e., they take the sure gain and do not gamble). But if the options are displayed in terms of a certain loss, subjects are more risk seeking (i.e., they rather gamble instead of taking the sure loss). Cassotti and colleagues (2012) were interested in whether a specific affective context (positive or negative) influences the framing effect in decision making. Based on previous studies, the authors hypothesized that positive affect (induced by positive affective pictures) enhances the focus on potential gain. This in turn should reduce the affective impact of a sure loss (in the loss frame), resulting in risk-averse decision making. In contrast, Cassotti and colleagues predicted that if a negative affect increases the focus on potential loss, an increase in risky decisions should be found in the loss frame. This is based on the assumption that negative affect enhances the affective influence of a sure loss. In order to measure the framing effect in decision making, Cassotti and colleagues used an adapted version of the gambling task of De Martino, Kumaran, Seymour and Dolan (2006). In this task participants were endowed with an amount of money ranging from €10 to €50 at the beginning of each trail. Furthermore, participants were informed that they cannot retain the whole amount, but would have to choose between a gamble and a sure option. Herby, the sure option would lead to a sure win or loss of a certain amount of money received initially. In contrast, in the gamble option participants were informed about a set probability to lose or keep the whole amount of the money received initially. Between the initial amount of money and the choosing part participants saw negative or positive pictures for a short interval (5000 ms). The results support the assumptions only in parts: Positive affect decreased risk propensity in the loss frame, while participants of the negative and neutral picture group still showed the framing effect.

In a study investigating the influence of affective states on the GDT (see Table 1 for a brief description of this task) as a measurement of decision making under risk (Bagneux, Bollon, & Dantzer, 2012; for a brief description of the task see Table 1), there was no distinction between positive and negative affect but between certainty-associated affect (e.g., anger or happiness) and uncertainty-associated affect (e.g., fear; for detailed information see the Appraisal-Tendency Framework of Lerner & Keltner, 2000). The induction of such affective states was done by presenting video clips before participants had to perform a modified version of the GDT (30 trials instead of 18). According to Lerner and Keltner (2000) certainty-associated affect lead to heuristic processing and uncertainty-associated affect encourage deliberative processing. In accordance with this, Bagneux and colleagues (2012) assumed that participants who watched the video clips inducing anger or happiness would rely more on heuristic processing (which takes affective information into account) and therefore use more strongly the feedback of previous decisions in the GDT, resulting in good decision-making performance. As opposed to this, participants who watched the video with fearful content should rely more strongly on systematic processing, leading to less use of the feedback and thus to disadvantageous decision making. The findings were in line with this assumption: Dividing the 30 trials of the GDT into five blocks, Bagneux and colleagues (2012) found that in the last three blocks participants who watched videos inducing anger and happiness chose the low-risk options more often than participants who saw the videos inducing fear. However, even though the difference slightly failed to reach significance, on a descriptive level the data display that there was a difference between positive (happy) and negative (anger) certainty-associated affect: Participants who watched the anger videos demonstrated better GDT performance compared with participants who watched the happy videos.

Overall, these findings demonstrate that in decisions under risk affective states influences decision-making performance differently compared to decision making under ambiguity (see section 3.4.2.2.1). While a negative affect increases risk aversion in decisions under risk (c.f. Heilman et al., 2010) it leads to inferior decision making under ambiguity (De Vries, et al., 2008b). Additionally, while a positive affective state leads, at least on a descriptive level, to inferior decision making under risk (c.f. Bagneux et al., 2012), it increases the decision-making performance in ambiguous decisions (De Vries, et al., 2008b). However, in decision under risk these influences interfere with other situational conditions, for instance framing effects (c.f. Cassotti et al., 2012), or the usage of experimental induced affect-regulation strategies (c.f. Heilman et al., 2010). Due to the special role of executive functions in decision making under risk (see section 3.2.2.2), the question remains whether executive functions could also moderate affective influences on decision-making performance. This is considered in the second study (chapter 5) of the present thesis, in which the possible interaction between decision making under risk while performing an additional task simultaneously, executive functions, and affective influences were analyzed.

A related topic to affect is stress. The origin of several affective states (e.g., anger, anxiety, hope, and relief) often lays in stressful situations. However, in the literature stress and affect were mostly investigated separately (Lazarus, 1993, 1999). Therefore, the following chapter is devoted to stress and its influence on decision-making processes.

3.4.3 Stress

Stress is a mental and bodily state that accompanies humans in everyday life and influences peoples' behavior, including decision making (for a review about stress and decision making see Starcke & Brand, 2012). However, before going into more detail on neurobiological correlates of stress and its influence on decision-making processes, in the following a short synopsis of the history of stress research will be given, which display the understanding of stress in the current thesis.

Since the 1930s stress is a constant field in psychological research and investigated in its many facets and in many different ways (for an overview see Schiebener, Staschkiewicz, et al., 2013; Starcke & Brand, 2012). A first understanding of stress was given by Hans Selye who defined stress as a general, nonspecific physiological response to a stressor (Selye, 1956). Hereby, a stressor was described as heat or cold while in the following decade the focus lied on cognitive factors (e.g., appraisals; c.f. Lazarus, 1999). In 1976 Selye specified his concept of stress by distinguishing between *eustress* and *distress*, whereby eustress was associated with positive feelings and healthy bodily states and distress with negative feelings and impaired bodily states (c.f. Lazarus, 1993; Selye, 1976). However, Seyle did not specify the physiological or psychological differences between those kinds of stress. This became more clear in the works of Lazarus (Lazarus, 1966, 1991a, 1993; Lazarus & Folkman, 1984; Lazarus & Launier, 1978). He differentiated between *challenge*, *harm*, and *threat.* According to Lazarus, challenge results from demanding situations, which a person feels confident about to overcome, and often leads to exhilarated feeling and expansive performance. In contrast, harm describes psychological damage that has already take place (e.g., death of a beloved person) and threat includes the anticipation of possible harm that has not yet taken place. Threat is described as an "unpleasant state of mind that may seriously block mental operations and impair functions" (Lazarus, 1993, p. 5). However, over the years studies have shown that it appears to be extremely difficult to dissociate these different kinds of stress (Koolhaas et al., 2011). Therefore, in the current thesis, there is no distinction between positive or negative stress. Stress is seen as an occurrence due to a discrepancy between an environmental, personal relevant demand (primary appraisal; Lazarus & Smith, 1988) and available resources to cope with it (secondary appraisal; Lazarus & Smith, 1988). In particular, unpredictable and uncontrollable situations seem to be experienced as stressful (Dickerson & Kemeny, 2004; Koolhaas, et al., 2011).

In order to get a better understanding of how stress is processed and may possibly interfere with decision-making processes, the following section will address the neuroendocrine and neural correlates of stress.

3.4.3.1 Neurobiological correlates of stress

It is postulated that stress processes bear on two neural systems of brain and body: The sympathetic adrenomedullary system (SAM-system; Cannon, 1914) that reacts fast and the hypothalamic pituitary adrenal axis (HPA-axis; Selye, 1956), which reacts slower. These two systems will now be outlined.

Within the SAM-system (see Figure 9), the neural stress reactions arise immediately after stress exposure: They originate in the hypothalamus and are conveyed via the sympathetic nuclei to the adrenal medulla. At this juncture, the catecholamines adrenaline and noradrenaline are released. In return, the catecholamines can enter the brain via the locus coeruleus. Here, projections reach the amygdala, the thalamus, the hypothalamus, the hippocampus and the PFC (review in e.g., Chrousos & Gold, 1992; De Kloet, Joels, &

Holsboer, 2005; Roozendaal, McEwen, & Chattarji, 2009). Moreover, the release of noradrenaline and adrenaline elicits different reactions of the sympathetic nervous system. For example, increases in electrodermal activity, blood pressure, and heart rate that occur directly after stress onset and return to baseline around 10 min after leaving the stressful situation (Het, Rohleder, Schoofs, Kirschbaum, & Wolf, 2009; Clemens Kirschbaum, Pirke, & Hellhammer, 1993). Catecholamines can be measured in the blood and by analyzing the enzyme alpha-amylase in saliva samples (Nater & Rohleder, 2009; Rohleder & Nater, 2009).

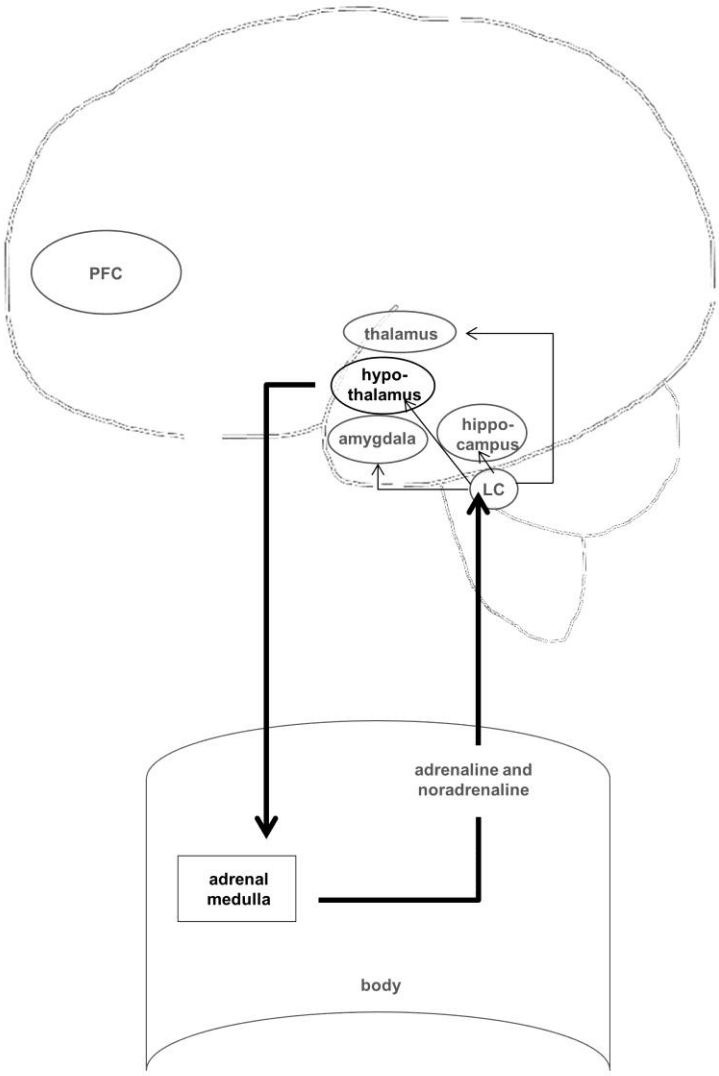

Figure 9 The sympathetic adrenomedullary system (SAM-system; Cannon, 1994).

The directly involved structures are accentuated. This figure is modified from Schiebener, Staschkiewicz et al. (2013). PFC = prefrontal cortex; LC = locus coeruleus.

Within the HPA-axis (see Figure 10), stress leads to a release of the corticotropin-releasing hormone of the hypothalamus. This causes a release of the adrenocorticotropic hormone of the pituitary that in turn stimulates the secretion of glucocorticoids (Sapolsky, Romero, & Munck, 2000). Various structures of the central nervous system are involved in the regulation of the HPA-axis: the amygdala, the hippocampus, and

parts of PFC (De Kloet, et al., 2005; Herman, Ostrander, Mueller, & Figueiredo, 2005). These are brain regions that possess a high density of receptors (mineralocorticoide-receptors/type 1 and glucocorticoid-receptors/type 2; review in Lupien, Maheu, Tu, Fiocco, & Schramek, 2007) to that glucocorticoids can bind. The major stress hormone in humans is cortisol. It elevates blood glucose levels to mobilize energy resources. It peaks approximately 21 to 40 min after a person encounters a stressful situation and returns to baseline level (i.e., before stressor) within 41 to 60 min (Dickerson & Kemeny, 2004). Cortisol can, among others, also be measured by analyzing the cortisol level in saliva samples (Clemens Kirschbaum & Hellhammer, 1994).

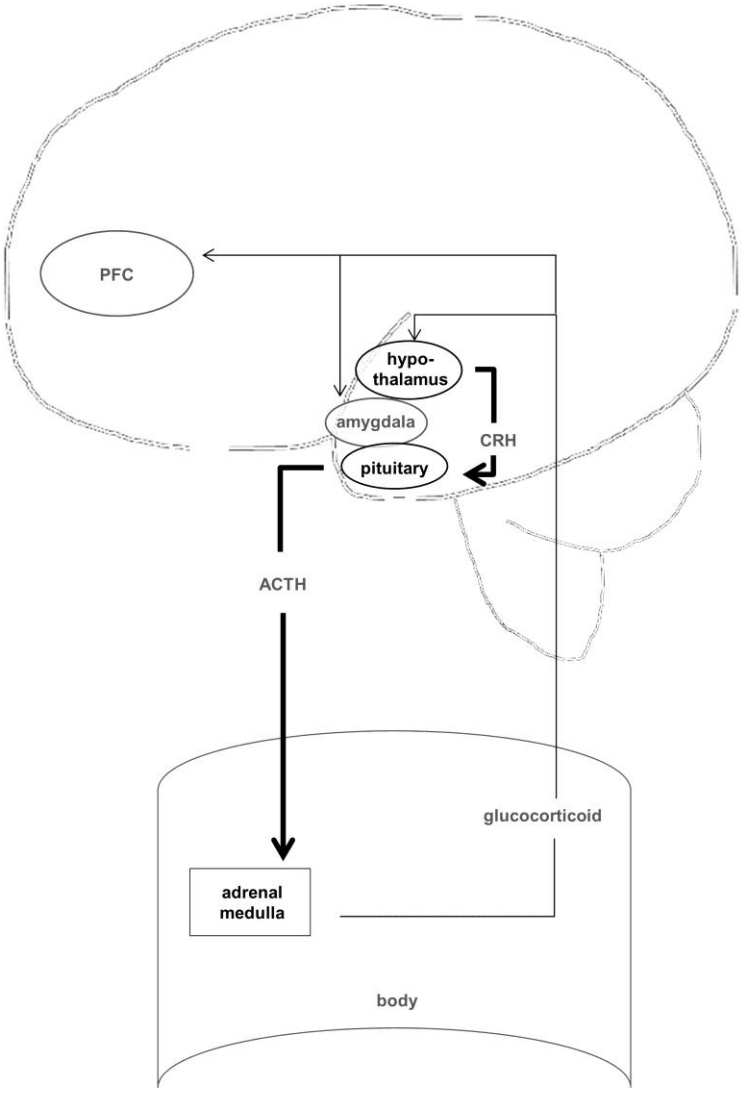

Figure 10 The hypothalamic pituitary adrenal axis (HPA-axis; Selye, 1956).

The directly involved structures are accentuated. This figure is modified from Schiebener, Staschkiewicz et al. (2013). PFC = prefrontal cortex; ACTH = adrenocorticotropic hormone; CRH = corticotropin-releasing hormone.

Furthermore, various neuroimaging studies investigating neural correlates of stress in healthy participants demonstrated metabolic changes in brain regions associated with a high density of glucocorticoids receptors. However, the results are heterogeneous. As can be seen in Table 3, some studies found an increase in

activity due to stress exposure in brain regions, like the ACC, the dlPFC, the cerebellum, and brain regions that are associated with the limbic system such as, the thalamus, and the insular cortex. In contrast, other studies found a decrease in activity due to stress in some of the same brain regions, for example, the ACC, the dlPFC, the OFC, and limbic related structures such as the hippocampus, the basal ganglia and the hypothalamus. These heterogeneous findings could be due to the fact that the studies differ in the paradigms used to induce and measure stress as well as in the time points of stress inducement and measurement (see Table 3). Therefore, the results are not directly comparable, and it remains unclear whether stress leads to an increased or decreased activation of prefrontal and limbic structures.

These mixed results can also be explained by interindividual differences in stress response (Kudielka, Hellhammer, & Wust, 2009). For example, it is consistently found that psychological stress paradigms (see section 3.4.3.2 for a few examples) lead to differences in cortisol response between men and women (Lovallo, Farag, Vincent, Thomas, & Wilson, 2006; Steptoe, Fieldman, Evans, & Perry, 1996). Although the pre-stress level did not differ, the cortisol increase after a psychological stress paradigm was found to be up to twice as high in men as in women (Clemens Kirschbaum, Pirke, & Hellhammer, 1995; C Kirschbaum, Wüst, & Hellhammer, 1992; Kumsta et al., 2007). Further factors that might influence the HPA-reactivity are age, use of oral contraceptive, chronic alcohol, or nicotine consumption. Therefore, it is important to control for these factors in stress research. However, there are many other factors influencing the stress reaction, which cannot easily be controlled, for instance, genetic factors, early life stress experiences, and personality. Therefore, the inability to control all of the factors that might influence stress response may lead to heterogeneous findings across studies (Kudielka, et al., 2009).

Overall, it becomes obvious that the brain regions involved in stress reactions, are also partially involved in decision making under ambiguity and risk (see section 3.3). The following sections will present studies investigating the interaction between stress and decisions under ambiguity and risk in healthy participants. First, however, an overview about possible stressors used in the laboratory to induce stress in participants, is given.

Table 3 Overview about the stressors, indicator of stress, and the time points of measurement and induction used in studies investigating the neural correlates of stress.

Study	Stressor	Time point of stressor	Indicator of stress	Time point of stress measurement	Imaging results
Critchley, Corfield, Chandler, Mathias, and Dolan (2000)	Serial subtraction	During PET session	Heart rate and blood pressure	During scanning	Increased activation in the ACC and cerebellum
Dedovic, Rexroth et al. (2009)	MIST	During fMRI session	cortisol	Before and during scanning	Increased activation in the dlPFC, the dorsomedial PFC, and temporal pole; Decreased activation in the hippocampus, medial OFC, and basal ganglia
Ito, Kanno, Hatazawa, and Miura (2003)	Serial subtraction	During fMRI session	Heart rate, blood pressure and arterial concentration of adrenaline, noradrenaline and dopamine	During scanning	Increased activation in the thalamus, insular cortex, ACC, cerebellum, superior temporal gyrus, inferior frontal gyrus, and angular gyrus
Koric et al. (2012)	Serial addition	During fMRI session	SAM	During scanning	Increased activation in the dlPFC
Pruessner et al. (2008)	MIST	During PET/fMRI session	Cortisol	Before, during, and after the scanning	Decreased activation in the hippocampus, hypothalamus, OFC, and ACC
Soufer et al. (1998)	Serial subtraction	During PET session	Heart rate and blood pressure	During scanning	Increased activation in the inferior frontal gyrus
Tillfors et al. (2001)	Public speech	During fMRI session	1) Heart rate 2) STAI, ratings of fear and distress	1) During scanning 2) After scanning	Increased activation in the insular cortex and temporal pole
Wang et al. (2005)	Serial subtraction	During fMRI session	Cortisol, heart rate, self-report	Before, during, and after scanning	Increased activation in the ventral PFC, ACC, and insular cortex

Note. The imaging results only include activation pattern from healthy participants, findings from patient groups are not mentioned. PET = Positron Emission Tomography, fMRI = functional Magnetic Resonance Imaging, MIST = Montreal Imaging Stress Task, SAM = Self-Assessment Manikin, STAI = State Trait Anxiety Inventory.

3.4.3.2 Laboratory stressors

In order to induce stress in the laboratory it is possible to administer stress hormones, like adrenaline and cortisol, which directly leads to physical stress reactions. Another common method is to use laboratory stressors that simulate natural stressors (Starcke & Brand, 2012). Such stressors might either be of a physical challenge (e.g., pain, heat, cold, exercise, inhalation of CO_2), a cognitive demand (e.g., analytical tasks, mental arithmetic, vigilance, or reaction-time tasks), or a social-evaluative threat (e.g., actual performance or anticipation of a public speech, direct or virtual observation of a person performing something, or verbal interaction). It is also possible to combine two or more stressors (e.g., mental arithmetic and public speech) (for a review see Dedovic, D'Aguiar, & Pruessner, 2009; Starcke & Brand, 2012).

An example of a physical challenge is the Cold Pressor Test (CPT; Hines & Brown, 1932). In the CPT, the hand of an individual is immersed into ice cold water for duration of one to three minutes (sometimes even longer). To the field of cognitive demands, belongs the serial subtraction or addition task, in which participants have to subtract or add a number e.g., 7 from/to a given 3- to 4- digit number (e.g., Ito, et al., 2003; Koric, et al., 2012). An example of a social-evaluative threat is the actual performance or anticipation of a public speech. Participants are asked to prepare a speech to a given topic. Thereafter they have to deliver the speech in front of an audience while they are videotaped. In the case of the anticipated speech participants do not have to deliver the speech (but this information is not given to the participants). A combination of social-evaluated threat and cognitive demand are the Trier Social Stress Test (TSST; Clemens Kirschbaum, et al., 1993) and the Montreal Imaging Stress Task (MIST; Dedovic et al., 2005). In the TSST, participants are asked to prepare and actually deliver a speech (similar to a mock job interview) in front of a committee, clothed with white coats, which behaves in a reserved and neutral way. After the speech, participants are asked to perform an arithmetic task as fast and accurate as possible, for example, counting backwards in steps of 17 starting with the number '2043'. During this whole procedure the participants are videotaped. In the MIST, participants are asked to perform challenging mental arithmetic tasks presented on a computer screen. Feedback is provided on screen ("correct" vs. "incorrect"). The difficulty of the tasks adapts to the participants performance such that a range of 20% to 45 % correct answers is enforced. A pseudo performance indictor informs the participants about their own and the other participants' average performance. Between experimental runs, participants are informed by the investigator that their individual performance has to be close to the average performance (80% to 90% correct answers) in order to be used in the study and the participants are told that their performance is monitored by the investigator and other participants.

To measure participants stress reactions, various stress indicators can be used. For example, it is possible to use the aforementioned saliva sample to analyze the cortisol, and alpha-amylase level (see section 3.4.3.1). Hereby, salivary cortisol is associated with slower HPA-axis activity (Dickerson & Kemeny, 2004), while salivary alpha-amylase mirrors the fast reactivity of the sympathetic nervous system, also SAM-system, (Nater & Rohleder, 2009; Rohleder & Nater, 2009). Furthermore, stress reactions can be measured by heart rate, blood pressure (e.g., Soufer, et al., 1998), but also through blood samples, which are used to analyze the stress hormone level (e.g., Ito, et al., 2003). Other measurements for stress reactions are self-reports and questionnaires, e.g., participants are asked to indicate their experienced level of anxiety and distress on a Likert scale. Common questionnaires used in stress studies are for example, the State Trait Anxiety Inventory (STAI;

Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1977), which measures acute anxiety reactions and the PANAS (Watson & Clark, 1999), which measures current affect.

3.4.3.3 The influence of stress on decision making

Most of the mentioned laboratory stressors were also used in order to induce stress in participants before they have to perform a decision-making task. This was done to examine the assumed negative influence on the decision-making performance. The following two sections will provide an overview about studies addressing decision making under ambiguity (section 3.4.3.3.1) or risk (section 3.4.3.3.2) in stressful situations in healthy participants.

3.4.3.3.1 Decision making under ambiguity in stressful situations

In the year 2007, Preston and colleagues were one of the first researcher groups investigating the influence of stress on the performance of decisions under ambiguity. They assumed that stress might interfere with task-related affect (somatic markers) that are necessary to make advantageous decisions in ambiguous situations. To test their assumption the authors conducted a study, in which participants were asked to perform the IGT two times (the first time the original version, the second time the repeat test version with different contingencies; for a brief description of the original version see Table 1). Before participants performed the IGT a second time, the experimental group was stressed while the control group sat quietly and waited until the second IGT performance began. For stress inducement Preston and colleagues (2007) used a social-evaluative threat, an anticipated public speech. Participants were asked to prepare a speech about what they like or dislike about their physical appearance. They were told that they would have to perform the IGT a second time within the next 20 min and that thereafter they would have to deliver the speech. However, after the participants had performed the repeat test version of the IGT they were debriefed that they would not have to deliver the speech. Stress reactions were measured via heart rate during both IGT performances. For this purpose, electrodes were attached at the participants' bodies. Moreover, STAI and PANAS were used to measure the current (affective) state of the participants. The self-report measurements were administered after arrival of the participants and a second time after the 50^{th} trial of both IGT versions. The results demonstrated that the stress induction was successful: Compared with the control group the experimental group showed higher anxiety and less positive affect in the self-report measures and a higher increase in heart rate. The increase in experienced stress influenced the decision-making performance: Across the 100 trials the participants of the experimental group learned the contingencies of the IGT more slowly than the control group. Furthermore, the results revealed an effect of gender. Stressed women chose from the advantageous card decks more often than unstressed women, while stressed men decided more disadvantageously than unstressed men. Preston and colleagues concluded that stress interferes with task-related affect and consequently leads to impaired decision making. However, gender appears to moderate these effects.

These results are supported by findings by Van den Bos, Harteveld, and Stoop (2009). While the authors also used the IGT in order to operationalize decision making under ambiguity, they induced stress using the TSST (for a short description of this test see section 3.4.3.2). Stress was induced before participants of the experimental group performed the IGT. In contrast, the control group listened to music or read magazines. Stress reactions were measured by analyzing the salivary cortisol concentration (see section 3.4.3.2) in both

groups. Thus, it was possible to classify the stress group in to high stress responders (i.e., participants with high cortisol responses) and low stress responders (i.e., participants with low cortisol responses). The data demonstrated again an effect of gender: Male high-responders decided more disadvantageously than male low-responders and control participants. Moreover, the correlative analysis revealed that higher cortisol concentration is associated with inferior decision-making performance. Conversely, female high-responders chose more cards from the advantageous decks and won more money in the second part of the game than low-responders and control participants, at least by trend. Furthermore, the correlative analysis revealed an interesting finding: An increase in cortisol concentration is associated with superior decision-making performance. However, very high cortisol concentrations lead to an increase in decision-making performance. Van den Bos and colleagues concluded that increased cortisol concentration as an indicator of stress reactions appears to influence decision making under ambiguity differently in men and women.

In total, it appears that stress impairs ambiguous decision making, especially in men. In contrast, women likely profit from stressful situations: Stressed women decide more advantageously than non-stressed women. The next section gives an overview about studies investigating the influence of stress in decision making under risk.

3.4.3.3.2 Decision making under risk in stressful situations

Regarding decisions under risk, several studies investigated the influence of stress on decision making using different decision-making tasks and various stressors and measurements of stress. This might have led to the heterogeneous findings reviewed here.

For example, studies using different modified versions of the CGT (see a brief description of the original version in Table 1) showed heterogeneous findings of the effect of stress on decision making under risk (Clark et al., 2012; Porcelli & Delgado, 2009; Putman, Antypa, Crysovergi, & van der Does, 2010). While Clark and colleagues (2012) found that stress leads to more risk-averse decision making, probably through an increase in processing loss information, the other two research groups found that stress increases risk-taking. Porcelli and Delgado (2009) revealed that in stressful situations participants choose more of the risky options especially in the loss domain (potentially negative outcomes), whereas they played more conservative in the gain domain (potentially positive outcomes). In comparison, stress in the study by Putman, Antypa, and colleagues (2010) led to risky decision making, in particular when this choice was associated with a potential high reward. As implied before, these contrasting findings might be due to different stressors and stress indicators used in those studies. For example, Clark and colleagues (2012) induced stress using the anticipation of an electric shock and for an indicator of stress they measured SCRs and heart rate. By contrast, Porcelli and Delgado used the CPT (for a short description of this test see section 3.4.3.2) for stress inducement. Stress reactions were measured with SCRs, too. Putman, Antypa, et al. (2010) induced stress by direct oral application of cortisol (capsule containing 40 mg cortisol) and collected saliva samples (see section 3.4.3.2) in order to measure cortisol level as stress reaction. Moreover, the STAI as a self-report measurement was administered. A further difference between those studies is that Putman, Antypa, and colleagues (2010) only investigated men, whereas the two other research groups investigated both men and women. Those factors could be reason for the heterogeneous findings. In total, studies investigating the influence of stress on decision making under risk, using various

modified versions of the CGT, found that stress influences decision-making performance, but whether stress leads to more advantageous or more disadvantageous decisions remains unclear.

There are also two studies investigating the effect of stress on decision making under risk using the BART (Lighthall, Mather, & Gorlick, 2009; Lighthall et al., 2012; see also Table 1 for a brief description of the task). In the first study (Lighthall, et al., 2009), stress was induced using the CPT before performing the decision-making task. Stress reactions were measured by analyzing cortisol concentration. Results revealed an effect of gender: Under stress, men became more risk-seeking while women became more risk avoidant. In a subsequent study Lighthall and colleagues (2012) were interested in the underlying brain mechanism of this gender-specific stress effect. Using the same stressors and indicators for stress reactions the authors found no differences in risk-taking between men and women. However, results revealed on a behavioral level that stress led to higher reward collection and faster decision-making speed in men but to lower reward collection and slower decision-making speed in women. Moreover, imaging data showed that regions associated with reward collection (the striatum and the insular cortex) were more activated in men than in women. Lighthall and colleagues (2012) suggested that the BART, which was used in an fMRI version in this study, could be the reason for not finding any sex-related differences in risk-taking. In this fMRI version participants did not need to take the risk and inflate balloons in order to earn more money; instead they could increase the decision-making speed and leave the balloons relatively small. In summary, stress appears to influence decision making in men and women differentially: While stressed men seem to be more risk-seeking and reward-collecting, they are also faster in decision making under risk than non-stressed men. Stressed women appear to be more risk avoidant, less reward-collecting, and slower in decision making under risk than non-stressed women.

Starcke and colleagues (2008) found that stress also influences GDT performance (see Table 1 for a brief description of this task). In their study the participants were told that before performing the GDT they would have to deliver a (anticipated) speech, discussing how they evaluate their cognitive abilities, in front of an audience and a video camera. By contrast, control participants were told to think about their last holiday. To assess stress reactions salivary cortisol and alpha-amylase were used as well as questionnaires (PANAS and STAI). The findings demonstrated that stressed participants were more anxious and had more negative affect after stress induction. Furthermore, they showed a significantly higher alpha-amylase increase than control participants. The cortisol increase was only higher on a descriptive level for stressed participants compared to control participants. Still, concerning decision-making performance, the results demonstrated that the stress group made more disadvantageous decisions than the control group. Moreover, a negative correlation between decision-making performance and cortisol increase was found. This indicates that a higher increase in cortisol is associated with more risky decision making. Analyses revealed no effect of gender. A further study using the GDT investigated how stress affects decision-making performance at different points in time (Pabst, Brand, & Wolf, 2013). Therefore, the GDT was administered at three different points in time resulting in three different experimental groups plus control group. To induce stress the TSST (for a short description of this test see section 3.4.3.2) was used. Stress reactions were measured using the PANAS as well as collecting salivary cortisol and alpha-amylase. The male participants were assigned to the four groups. In group one the participants performed the GDT after they had prepared the speech they would have to deliver (5 min after baseline measurement). Participants of the second group performed the GDT right after the TSST (18 min after baseline measurement), while the third group had to wait additional 10 min before performing the GDT (28 min

after baseline measurement). The control group performed the GDT at the same time point as the second group (18 min after baseline measurement). However, the control group was not stressed. Instead, they had to rest before they were asked to perform the GDT. In summary, the results revealed that acute stress has a time dependent effect on the decision-making performance. The first and the second group, which performed the GDT earlier than the third group, demonstrated superior decision-making performance, than the third group and the control group. In contrast, descriptively, the third group showed more disadvantageous decisions than the control group. This indicates that fast sympathetic reactions (increase in salivary alpha-amylase that suggests increased catecholamine like noradrenaline and dopamine) lead to improved decision making while slower HPA-axis related reactions (increase in salivary cortisol) appears to lead to inferior decision-making performance.

Overall, stress influences decision making under risk. However, while some studies found effects of gender other did not. Moreover, findings are heterogeneous regarding the fact whether stress leads to impairment or to improvement of decision-making performance. Besides the fact that this might be due to different stressors used and different stress reaction measurements, studies using the GDT demonstrated that this might also be a time depended effect, with superior decision-making performance at the beginning of a stressor and inferior performance later on. So far, the studies mentioned above only addressed one situational influence on decision making at a time that means either additional cognitive demand (see section 3.4.1) or additional affective influence (see sections 3.4.2 and 3.4.3). The question remains what happens with the decision-making performance when both processing routes (cognitive and affective) are demanded by decision making irrelevant claims simultaneously. The following section will address this matter.

3.4.4 Additioinal cognitive and affective influences and the interaction with decision making under risk

So far, each situational influence and its effect on decision-making performance, was addressed individually. Particularly in decision making under risk it was shown that additional executive demand leads to inferior decision making, as well as affective influences, especially stress (see sections 3.4.1.4.2, 3.4.2.2.2, and 3.4.3.3.2). However, in everyday life a situation provides many situational influences in combination (see the example in section 2, in which the student has an exam, missed the train and now needs to reschedule the departure while simultaneously deciding whether she/he will get in time to the university to take the exam). The remaining question is: What would happen to the decision-making performance when both processing routes (the cognitive and the affective route) are demanded simultaneously while having to decide. Due to the fact both routes interact in decision-making processes it appears plausible that this will lead to impairments in performance.

A recent study addressed this question and examined the interaction between stress, decision making under risk, and additional executive load (Pabst, Schoofs, et al., 2013). For this purpose participants had either to perform the GDT plus an additional 2-back task or the GDT solely. Moreover, half of the participants of each condition (GDT plus 2-back vs. GDT) were stressed before task performance. For stress induction the TSST was used. Stress reactions were measured by the PANAS as well as salivary cortisol and alpha-amylase. It was hypothesized that the combination of stress and additional task would lead to an even substantial impairment of decision making. The results showed that each condition alone (i.e., participants performing the GDT solely

after being stressed and participants performing the GDT plus 2-back task without being stressed before) led to the well-known decrease in disadvantageous decision making in the GDT (c.f. Starcke, et al., 2011; Starcke, et al., 2008; see also section 3.4.1.4.2). Interestingly, the combination of both (stress and additional task) revealed no decision-making impairments. Stressed participants performed the GDT in the dual-tasking condition similar to non-stressed participants performing the GDT solely. This appears to be paradoxical, but Pabst, Schoofs, and colleagues (2013) argue that this might be due to stress induced cognitive shift from serial to parallel processing: According to Starcke and colleagues (2011) both tasks (GDT and 2-back task) require the same cognitive processes, which belong to system 2. Therefore, both tasks need to be processed serially (Evans, 2003; Kahneman, 2003). In the frame of dual-process theories and dual-tasking approaches this means that concentrating on one task set, results in inhibition of information of the second task set (Koch, Gade, Schuch, & Philipp, 2010), which again narrows the attention of the participants to the particular tasks and subsequently shielding the task from competing distractors (see Easterbrook, 1959). Simultaneously, it enables participants to monitor task performance for potential second-task-associated action information, in order to switch to this task if necessary (Miller & Cohen, 2001; Plessow, Fischer, Kirschbaum, & Goschke, 2011). If acute stress is induced in this kind of dual-tasking situations it was shown that it did not impair task performance (see also Schwabe, Schächinger, de Kloet, & Oitzl, 2010), but that it decreases task shielding (Plessow, et al., 2012). Plessow and colleagues (2012) assumed that decreasing task shielding enables a cognitive shift from a serial to parallel goal monitoring enabling the performance of both tasks. Furthermore, they suggest that stress triggers a less resource-demanding processing mode (see also Arnsten, 2009; Schwabe, Wolf, & Oitzl, 2010). It is assumed that in a single-task situation the less resource-consuming task-processing mode is associated with tonic task shielding (Lehle, Steinhauser, & Hübner, 2009), which was shown to be increased under acute stress (Plessow, et al., 2011). In dual-task situations, however, the less resource-consuming processing mode is associated with a reduction of task shielding that increases parallel processing (Lehle, et al., 2009). Consequently, Pabst, Schoofs, and colleagues (2013) argue that in their study stress may also have triggered a serial-to-parallel processing mode in the dual-tasking condition, in which parallel performance is advantageously for inferior task performance. Besides this finding, it was also found that executive functions (i.e., divided attention) appear to moderate this influence: When performing the GDT solely participants with low divided attention ability decided disadvantageously in the condition without stress and even worse in a stressful situation. In contrast, participants with high divided attention ability performing the GDT plus 2-back task showed improved (low risk) decision making under stress than those without. However, stress did not influence the decision-making performance in participants who have a high ability to divide attention when they performed the GDT solely. Likewise, when participants had a low ability to divide their attention they showed disadvantageous decision making, regardless whether they were stressed before or not. In summary, while studies using the GDT solely have shown that stress seems to impair the decision-making performance, a simultaneous induced cognitive demanding load due to an additional executive task, does not lead to an increased impairment. In contrast, a combination of both manipulations seems to cancel out the negative effects of each single condition. Furthermore, executive functions appear to moderate the influence of stress on such demanding situations.

Still remaining is the question of the underlying neural correlates of the interaction between stress, decision making under risk, and additional executive load. What happens in the brain that enables participants to decide advantageously although both processing routes (cognitive and affective route) are demanded otherwise?

Study 1 of the present thesis was conducted to address this question in detail and to contribute to enlarge the knowledge about processing mechanisms of the human brain in demanding decision-making situations.

3.5 Conclusion from theoretical background

Reviewing the literature of the neuropsychological decision-making research revealed that there is a broad knowledge about the underlying cognitive and affective processes as well as about the associated neural correlates. Yet, about the interaction between cognitive and affective processes in decision making and the associated neural correlates little is known. In particular, in decision making under risk it is of interest to investigate such interaction in more detail, since it was shown that a demand on the cognitive route alone (see section 3.4.1.4.2) as well as a demand on the affective route solely leads to impaired decision making (see sections 3.4.2.2.2 and 3.4.3.3.2), but a demand on both routes simultaneously does not affect decision-making performance (see section 3.4.4). The first study of this thesis aims to investigate the underlying neural correlates of the interaction between stress (as affective demand), additional cognitive demand and decision making, in order to enlighten this paradoxical appearing effect. Due to the fact that it was shown that varying valence of affect influences decision making under risk differentially (see section 3.4.2.2.2), the second study aims to investigate the effect of affective influences of varying valence on decision making in situations with additional cognitive demand. Moreover, studies have shown that cognitive functions may compensate each other in case one function is impaired as well as they appear to compensate impairments of the affective route, in order to prevent decision-making performance from decreasing (see sections 3.1.2.2, 3.2.2.2, and 3.4.4). Therefore, a possible moderation effect of cognitive functions, such as executive functions, on the affective influence on decision-making performance in situations with additional cognitive demand will also be examined in study 2. According to dual-tasking approaches a supervisory/ monitoring function is needed to perform two tasks simultaneously (see section 3.4.1). However, regarding decision making various studies have demonstrated that executive functions, for instance categorization and feedback processing, are involved in order to decide advantageously (see section 3.2.2.2). The last study of the current thesis aimed to analyze which specific executive functions are involved in this kind of dual-tasking situation, where a decision needs to be made while another executive task needs to be performed simultaneously. Gaining knowledge about the executive functions involved in such situations may firstly extend understanding the role of executive functions in decision making per se and secondly in demanding decision-making situations in particular.

4. Study 1: Stress and decision making: Neural correlates of the interaction between stress, executive functions, and decision making under risk

4.1 Abstract

Stress and additional load on the executive system, produced by a parallel working memory task, impair decision making under risk. However, the combination of stress and a parallel task seems to preserve the decision-making performance (e.g., operationalized by the GDT) from decreasing, probably by a shift from serial to parallel processing. The question remains how the brain manages such demanding decision-making situations. The current study used a 7-tesla magnetic resonance imaging system in order to investigate the underlying neural correlates of the interaction between stress (induced by the TSST), risky decision making (GDT), and a parallel executive task (2-back task) to get a better understanding of those behavioral findings. The results show that on a behavioral level, stressed participants did not show significant differences in task performance. Interestingly, when comparing the stress group (SG) with the control group, the stress group (SG) showed a greater increase in neural activation in the anterior PFC (aPFC) when performing the 2-back task simultaneously with the GDT than when performing each task alone. This brain area is associated with parallel processing. Thus, the results may suggest that in stressful dual-tasking situations, where a decision has to be made when in parallel working memory is demanded, a stronger activation of a brain area associated with parallel processing takes place. The findings are in line with the idea that stress seems to trigger a shift from serial to parallel processing in demanding dual-tasking situations.

4.2 Introduction

Decision making is a key function in human everyday life. Sometimes, decisions are less important, without far-reaching consequences, and easy to make such as which clothes to wear or which meal to cook. However, in some situations, people have to make decisions with potentially severe consequences, for example, a doctor in the operating room, a policeman during a street fight, or a stock market trader who has to decide which company shares to buy or to sell. These situations often elicit psychological stress, which could have an influence on the decisions people make. Additionally, these situations often require making more than one decision at the same time. In these situations, people have to make crucial decisions in a stressful setting while working on another problem simultaneously. It is important to understand what happens to peoples' decision-making performance in such situations.

As described in detail in section 3, the field of neuropsychological decision-making research distinguishes between decisions under ambiguity and decisions under risk (Brand, et al., 2006). In contrast to decision making under ambiguity, in decisions under risk, the decision maker has knowledge about the probabilities of different potential outcomes – or the probabilities are explicitly provided – and can largely estimate the possible consequences (Brand, et al., 2006). An often used task to measure decision making under risk is the GDT (for a brief description of this task see Table 1). A recent study using this task investigated the interaction between stress, decision making under risk, and additional executive load (Pabst, Schoofs, et al., 2013; a more detailed description of this study is given in section 3.4.4). The participants were divided into four groups: a stress group and a control group performing only the GDT (single-task condition) and a stress group

and a control group performing the GDT plus an additional working memory 2-back task (dual-task condition). Pabst, Schoofs, and colleagues (2013) found that while stress led to diminished GDT performance in the single-task condition, in the dual-task condition stress seems to preserve the decision-making performance from decreasing, resulting in comparable GDT performances in the dual-task condition and in the single-task condition. However, when comparing the decision-making performance between the two control groups, they found that participants performing the additional 2-back task in parallel made more disadvantageous decisions than participants performing the GDT by itself. These results are in line with previous studies demonstrating negative influence of stress on GDT performance (Starcke, et al., 2008) and diminished decision-making performance while performing a secondary executive task simultaneously (Starcke, et al., 2011). Still, of more interest is the fact that stress combined with a parallel executive task seems to retain good decision-making performance. As discussed in section 3.4.4 in detail, Pabst, Schoofs, and colleagues (2013) assumed that stress triggers a cognitive shift from serial goal monitoring to parallel goal monitoring, which is a less resource-consuming mode for dual tasking (Lehle, et al., 2009). Consequently, leading to preserved performance in the decision-making task. The question remains what happens in the brain in such demanding situations and which brain areas are involved.

Neuroimaging studies investigating the underlying neural mechanisms of decision making under risk found brain areas associated with executive functions (the dlPFC, the ACC, and parts of the posterior parietal lobe) as well as areas associated with affective processing (the vmPFC/OFC and limbic structures) to be involved in decision making under risk (see section 3.3 for detailed information about the neural correlates of decisions under risk). These findings fit nicely with the results of a recent fMRI study by Gläscher and colleagues (2012), demonstrating that the aforementioned brain areas are involved in two functional-anatomical pathways: a cognitive one, which includes the dlPFC and the ACC, and a value-based one, which includes, among others, the vmPFC/OFC. These findings support the assumption by Brand and colleagues (2006) that beyond the necessity of the cognitive pathway, affective processing is also involved in decision making under risk (for more information see sections 3.1.2.2 and 3.2.2.2). Studies comparing the decision-making performance of healthy control subjects with patients who have lesions or dysfunctions to limbic and prefrontal brain areas support these findings by demonstrating that these patients made more disadvantageous decisions in the GDT (e.g., Brand, Fujiwara, et al., 2005; Brand, Grabenhorst, et al., 2007; Delazer, et al., 2007; Drechsler, et al., 2007; Euteneuer, et al., 2009; Fond, et al., 2012; Svaldi, et al., 2012).

Studies addressing the neural correlates of stress revealed heterogeneous findings. Some studies found that stress leads to deactivation in brain regions such as the OFC (Pruessner, et al., 2008; Tillfors, et al., 2001) and other regions associated with the limbic system such as the hippocampus and the hypothalamus (Dedovic, Rexroth, et al., 2009; Pruessner, et al., 2008), the ACC (Åhs et al., 2006; Pruessner, et al., 2008), and the dlPFC (Åhs, et al., 2006; Oei et al., 2007; Pruessner, et al., 2008; Qin, Hermans, van Marle, Luo, & Fernández, 2009). In contrast, other studies demonstrated an increase in some of the same brain regions during stress exposure: the ACC and the dlPFC (Dedovic, Rexroth, et al., 2009; Tillfors, Furmark, Marteinsdottir, & Fredrikson, 2002; Wang, et al., 2005), and limbic-related structures such as the hippocampus, the amygdala, the thalamus, and the insular cortex (Ito, et al., 2003; Tillfors, et al., 2002; Wang, et al., 2005). Results are not consistent, and it remains unclear whether stress leads to an increased or decreased activation of prefrontal and limbic structures (see section 3.4.3.1 for further information regarding the heterogeneity of the findings). Apart from this, it is

assumable that because decision making and stress reactions are associated with overlapping brain areas, stress can modulate decision making as discussed before (see also the review by Starcke & Brand, 2012). However, no study investigated the underlying neural correlates of the interaction between stress, decision making, and an additional executive load. What are the neural correlates of the suggested shift to a parallel goal monitoring and thus to advantageous decision making in dual-task situations as described by Pabst, Schoofs, and colleagues (2013)?

The present study was conducted in order to close this gap. We used the same task paradigm used in the study by Pabst, Schoofs, and colleagues (2013) but modified for fMRI. In one group, stress was induced before the scans, while a second group served as control group. In order to compare GDT performance with GDT plus 2-back performance, all participants had to perform single-task and dual-task conditions. At behavioral level, we assumed to replicate the findings by Pabst, Schoofs, and colleagues that acute stress in combination with a parallel executive task leads to preserved decision-making performance. Concerning the neural correlates, we hypothesized for the control group that dorsolateral prefrontal areas as well as parts of the ACC would be activated in particular during the GDT plus 2-back task (contrasts: GDT plus 2-back>; GDT plus 2-back > GDT; GDT plus 2-back > 2-back; GDT plus 2-back < GDT; GDT plus 2-back < 2-back), given that these regions are activated when a person processes gains/losses in combination with winning probabilities and also in a working memory paradigm (Labudda et al., 2010; Labudda, et al., 2008; Owen, et al., 2005). Of special interest was the comparison between the stress group and the control group, concerning the difference in activations between a dual-task condition and a single-task condition. We hypothesized that stress would lead to changes in neural activity in brain areas also involved in task performances that means, dorsolateral prefrontal areas and parts of the ACC. Moreover, we assumed that the shift from serial to parallel processing is associated with the same brain areas. This was assumed because those regions are known to be involved in the executive control mechanisms (Alvarez & Emory, 2006; D'Esposito, et al., 1995), which in turn are presumed to be engaged in the serial-to-parallel shift. Studies with similar types of stressors (Åhs, et al., 2006) as well as comparable points in time when the stressor takes place (before fMRI and before a cognitive task, Åhs, et al., 2006; Oei, et al., 2007; Qin, et al., 2009) displayed deactivation in the dlPFC and the ACC. However, because several studies were also able to demonstrate an increase in these brain areas during stress (Dedovic, Rexroth, et al., 2009; Tillfors, et al., 2002; Wang, et al., 2005), the neural activity changes will be analyzed in both directions (contrast for increase in activation: stress group > control group, GDT plus 2-back > GDT alternatively 2-back; contrast for decrease in activation: control group > stress group, GDT plus 2-back > GDT alternatively 2-back).

4.3 Methods

4.3.1 Participants

We examined 38 right-handed, healthy participants. The participants were randomly assigned to either the stress group (SG; $n = 19$) or the control group (CG; $n = 19$). Exclusion criteria, as determined by telephone screening, were history of or current neurological or psychiatric diseases, acute or chronic diseases, and stressful life circumstances. Smokers and participants with current intake of medication, body mass index above 30 kg/cm² or lower than 18 kg/cm², recent immunization, hormonal contraceptive, or pregnancy were excluded because these

criteria influence the measurement of stress hormones. Further exclusion criteria concerned issues interfering with the magnetic field of the fMRI such as active implants, mechanical contraception, or any metal objects that were not removable from the body. A further exclusion criterion was claustrophobia. Additionally, participants were requested not to engage in exhausting physical activities at least 24 hr before the testing, to refrain from drinking alcohol at least 24 hr before the testing, and to wake up at least 2 hr before the testing. Furthermore, all participants were instructed not to eat or drink anything other than water 1 hr before and during the study. All participants were recruited by advertisements and were paid €10/hr for participation. Student participants obtained credits for courses. Participants gave written informed consent prior to the investigation. After participation, they were fully debriefed about the aim of the study. The study was approved by the ethics committee of the German Society of Psychology. Due to problems in data acquisition, because of software malfunctions, artifacts in salivary samples, and one participant dropping out of the scanning session, the final groups consisted of $n = 16$ in the SG and $n = 17$ in the CG. The two groups did not differ regarding gender, SG: 9 men and 7 women, CG: 8 men and 9 women, $\chi^2 = 0.28$, $df = 1$, $p = .598$, or age, $M_{SG} = 23.69$, $SD_{SG} = 5.00$, $M_{CG} = 24.06$, $SD_{CG} = 5.07$, $t = 0.21$, $df = 31$, $p = .834$. Moreover, all participants started the experiment between 9:30 am and 6:00 pm, and there was no significant difference in starting time between the groups, $\chi^2 = 2.22$, $df = 3$, $p = .528$. There was also no difference between groups in the number of participants who started in the mornings (9:30 am and 11:40 am) and those who started in the afternoons (1:20 pm and 3:00 pm), $\chi^2 = 0.79$, $df = 1$, $p = .373$.

4.3.2 Stress induction

Stress was induced using the TSST (Clemens Kirschbaum, et al., 1993). This test is an established procedure that induces moderate psychosocial stress and a distinctive activation of the HPA-axis (see also section 3.4.3.2). In the TSST, participants had to deliver a free speech (after a preparation time of 5 min) followed by a demanding arithmetic task in front of a selection committee, each part lasting 5 min. The members of the committee were dressed in white lab coats and were introduced as psychologists who were specially trained to analyze speech and non-verbal behavior. Furthermore, it was announced that the speech will be video recorded. During the whole speech, the committee acted in a cold and non-responsive manner. In the non-stressful control condition, the standardized control version of the TSST (placebo TSST; Het, et al., 2009) was used. Here, participants also had to deliver a speech but not in front of a committee. They were alone in a room, not video recorded, and the arithmetic task was easier.

4.3.3 Measurements of stress response

4.3.3.1 Salivary cortisol

Endocrine indicators of stress were acquired by collecting salivary cortisol (for a description of the characteristics of saliva cortisol see section 3.4.3.1). A rise of cortisol concentration indicates the stress response due to HPA-axis activity (see Dickerson & Kemeny, 2004). Saliva was sampled five times (see the section 4.3.6.1) using Salivette collection devices (Sarstedt, Nuembrecht, Germany) and was sent to the laboratory of Prof. Kirschbaum in Dresden, Germany, for analysis. An immunoassay (IBL, Hamburg, Germany) was used to measure free cortisol.

4.3.3.2 Positive and Negative Affect Schedule (PANAS)

The PANAS (Watson, Clark, & Tellegen, 1988) was administered to measure the self-experienced stress level. In the German version of the PANAS, participants were asked to rate 10 items for positive affect (e.g., "elated" and "excited") and 10 items for negative affect (e.g., "distressed" and "hostile") on a five-point scale from 1 (*very slightly or not at all*) to 5 (*extremely*). The answers are added up to a positive affect score and a negative affect score, both ranging from 10 (minimum) to 50 (maximum).

4.3.4 Functional Magnetic Resonance Imaging (fMRI)[1]

FMRI is a noninvasive imaging technique, which provides the opportunity to visualize structural (i.e., anatomical images of a brain region) and functional data (i.e., images which display increases/decreases of brain activity) without the use of radiation (Bandettini, Wong, Hinks, Tikofsky, & Hyde, 1992; Goebel, 2007; Kwong et al., 1992). It is a modification of the anatomical *magnetic resonance imaging* (MRI), which is able to provide detailed anatomical images of, for example, gray and white matter in the brain. These images are used to localize the functional results, which presents themselves an increase or decrease of brain activity due to for example, stimuli presentation (Wager, et al., 2007). This neural brain activity is linked to changes in regional blood flow and the associated oxygen concentration (Stippich, 2007; Wager, et al., 2007).

4.3.4.1 Physical principles of magnet resonance imaging (MRI)

FMRI is based on the excitation and measurement of an electromagnetic echo of the participants' tissue. Each biological organism consists of a high density of water atoms, which are the largest source of protons in the body. Protons can be magnetized easily: Each proton spins around its own axis and thus induces its own magnetic field. Normally, the magnetic field of each proton is randomly aligned in the human body, which leads to a mutual neutralization and consequently the human tissue provides no magnetizable features. However, as soon as a person enters the magnetic field of the MRI system, the magnetic fields of the protons align with the magnetic field of the MRI system (Goebel, 2007; Goebel & Kriegeskorte, 2005b; Wager, et al., 2007). Through a short impulse of a radio frequency (released by e.g., a head coil which surrounds the head of a participant or the radio frequency coil) it is possible to excite the protons: They are briefly taped; thereafter they tip back (*relax*) into the alignment of the magnetic field of the MRI system. While the protons relax they emit a radio frequency, the electromagnetic echo, which is the magnetic resonance signal (MR-signal). The MR-signal is received by a receiving coil, for example the head coil. The relaxation process can be described by three parameters (see Goebel, 2007; Goebel & Kriegeskorte, 2005b; Wager, et al., 2007 for detailed information): T_1, T_2 and T_2^*. T_1 (also known as longitudinal relaxation or spin-lattice relaxation) determines the rate at which protons relax back to the alignment of the magnetic field of the MRI system. The magnetization increases in this period. T_2 (also known as transversal relaxation or spin-spin relaxation) refers to the duration in which the spins (tipped protons) exchange energy with each other, because of their own originated magnetic field. Due to this exchange the protons dephase (i.e., the transversal alignment to the extern magnetic field, induced by the radio frequency pulse, is lost). This is associated with loss of transversal magnetization and loss of the MR-signal. The transversal relaxation occurs faster in physiological tissues because of local inhomogeneity of the magnetic

[1] This section is not part of the original paper (c.f. Gathmann, Schulte, et al., 2014). It was added in the current thesis to give a comprehensive description of the imaging procedure used.

field. The resulting shorter time component is labeled T_2^*. The originated MR-signal is intercepted outside the human body and converted into three-dimensional pictures, which are sensitive to the different relaxation times: T_1-weighted images and T_2-weighted images are used for high-resolution structural scans. T_2^* is sensitive to blood flow and oxygenation and therefore T_2^*-weighted images reflect changes in brain activity (Goebel, 2007; Goebel & Kriegeskorte, 2005b; Wager, et al., 2007). For detailed information about the physical basics of (f)MRI be kindly referred to Bandettini, Birn, and Donahue (2000) and Huettel, Song, and McCarthy (2009), for detailed information about the generation of magnetic resonance images see Elster (1994).

A particular goal of fMRI is to capture functional changes in neural activity that is associated with specific functions (e.g., motor response). This is assessed indirectly via the hemodynamic response (Menon et al., 1995): An increase of neuronal activity in a certain brain area leads to an immediate increase of the extraction of oxygen-rich blood (oxygenated hemoglobin) within the capillary bed, which in turn increases oxygen-depleted (deoxygenated hemoglobin) blood. This fast response (*initial dip*) is followed by a strong local blood flow and consequently to an increase of oxygenated blood, which is referred to as hemodynamic response (Goebel, 2007). The hemodynamic response is so strong that it even results in a local oversupply of oxygenated hemoglobin (P. T. Fox & Raichle, 1986). One method which is used in fMRI to indirectly measure the neural activity is to adopt the *blood oxygen level dependent* (BOLD) effect (Ogawa, Lee, Kay, & Tank, 1990; Ogawa et al., 1993). The BOLD effect implies that the ratio of oxygenated and deoxygenated hemoglobin influences the MR-signal: Deoxygenated hemoglobin is paramagnetic (more magnetic) and thus leads to local inhomogeneity of the magnetic field (Ogawa, et al., 1990). In contrast, the oxygenated hemoglobin is diamagnetic (Ogawa, et al., 1990) that means, less magnetic. Therefore, the increase of the oxygenated hemoglobin during the hemodynamic response diminishes the inhomogeneity of the magnetic field. This entails that the positrons dephase more slowly after excitation, which leads to a stronger T_2^*-weighted MR-Signal (Goebel, 2007; Goebel & Kriegeskorte, 2005b). In summary, the BOLD effect "measures increased neuronal activity indirectly via a change in local magnetic field (in)homogeneity, which is caused by an oversupply of oxygenated blood" (Goebel, 2007, p. 18). How exact or detailed the brain tissue is measured depends on the magnetic field strength of the fMRI-system.

4.3.4.2 Procedures of functional data analysis

The functional data can then be analyzed using statistical programs such as statistical parametric mapping (SPM8, Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm). In the course of this the raw data need to be processed substantially to stick to the assumptions on which most analyses are based (Goebel, 2007; Wager, et al., 2007). During fMRI measurement the brain is scanned in slices along three axes: x-axis (sagittal slices), y-axis (coronal slices), and z-axis (axial slices). These data must first be transformed into a 4-D matrix: a sequence of functional volumes (3-D images) (Goebel, 2007). This step is known as *reconstruction* (Wager, et al., 2007). In the next step (*slice timing*) all slices need to be brought into one time zone, because it is assumed that each slice is scanned at the same time. However in reality all slices are shifted in time. To comply with the assumption that over time each data point from a given *voxel* ("voxel = volume element analogues to pixel = picture element"; c.f. Goebel, 2007, p. 23) was collected from that voxel only, a correction for movement for each participant needs to be done (*realignment*). The next step is called *smoothing*: At this time, all images are convolved with a *Gaussian kernel* (a 3-D normal probability density

function, c.f. Wager, et al., 2007) to uphold the assumption that the noise in all images conform to a normal distribution (c.f. Gaussian random field (GRF) theory; for detailed information about the role of the GRF theory in spatial smoothing be referred to e.g., Goutte, Nielsen, & Hansen, 2000; Worsley & Friston, 1995). Finally, it is important to make sure, that all image localizations in the structural and functional data correspond to the same brain region for each participant (*co-registration*) and between all participants (*normalization and warping*) (c.f. Wager, et al., 2007). Thereafter, preprocessing is finished and the images can be used for inferential statistics in terms of general linear modeling (GLM; see e.g., Goebel, 2007; Goebel & Kriegeskorte, 2005a; Wager, et al., 2007). At this point it is possible, for example, to calculate differences in brain activity in one brain region between groups (for a detailed description about several statistical analyses of the imaging data please be referred to Goebel, 2007; Goebel & Kriegeskorte, 2005a; Wager, et al., 2007).

4.3.5 The functional magnetic resonance imaging (fMRI) paradigm

In the fMRI within-subject design of the current study, three different experimental tasks were used: an fMRI version of the original GDT (see description in Brand, Fujiwara, et al., 2005; and Table 1), the GDT plus a parallel 2-back task (c.f. Starcke, et al., 2011), and a single 2-back task (c.f. Schoofs, Preuß, & Wolf, 2008). The experimental conditions are described in detail below. All experimental conditions had the same visual input in terms of screen organization and screen content. When performing the GDT alone, the interface of the 2-back task was frozen, showing one number that did not change. In contrast, when performing the 2-back task alone, the GDT interface was frozen, although the dice cup was being shaken. In the GDT plus 2-back task, the whole screen was activated. Each experimental condition lasted 144 s (for a detailed description of the tasks, see section 4.3.5.1). Moreover, two control tasks were used to normalize the BOLD (Ogawa, et al., 1990; see also section 4.3.4.1) signal (back to baseline) and to avoid carry-over effects of activation between the experimental conditions. In the high-level control task, participants were asked to indicate in which line a number or a number combination was highlighted. The duration was 144 s, and the task was performed twice. The order of the tasks was pseudo-randomized to minimize adaption to the tasks. The low-level control task lasted 30 s and was administered before an instruction window appeared (for 10 s) that provided a short summary of the ensuing experimental task and the upcoming high-level control task. Additionally, the low-level control task was administered after the last task in the scanning session. The total duration of the study was 26.5 min. The two orders of the tasks were counterbalanced across groups. The fMRI data of each task were assembled, and the behavioral data for each task were averaged for both runs for analysis. To register the answers of the participants, they held two four-touch keypads in their hands. The keypad in the left hand was associated with the 2-back task and with the low-level control task. The keypad in the right hand was associated with the GDT and the high-level control task. To indicate the answers for the GDT plus 2-back task, both keypads had to be used simultaneously.

4.3.5.1 Experimental conditions

We designed an fMRI version of the GDT based on the original GDT (Brand, Fujiwara, et al., 2005; the task is also briefly described in Table 1) to measure decision making under risk for the first experimental condition. The goal of this task was to increase the fictitious starting capital of €1,000. A virtual die was thrown 18 times, and the participants were asked to guess each time which number would be thrown. Participants could bet either

on one single number or on combinations of two, three, or four numbers, each associated with different winning probabilities: The choice of a single number provided a €1,000 gain/loss (winning probability 1:6); the choice of one of the other combinations provided a €500 gain/loss for two numbers (winning probability 2:6), a €200 gain/loss for three numbers (winning probability 3:6), and a €100 gain/loss for four numbers (winning probability 4:6). Even though the options were permanently shown on the screen, in this fMRI version of the GDT the participants were able to choose only one option of each possible category (one for each degree of risk). The available options were highlighted and pseudo-randomized across trials. This was performed to reduce the complexity of the game as well as to reduce artifacts in brain activation due to finger/hand movements, which would have been likely if participants had to select one of the alternatives with the mouse, as it is the case in the original GDT. In our fMRI version, participants had to indicate their answer on a four-touch keypad in the right hand, where each button was associated with one category. Furthermore, the decision time was limited to 4 s. If participants did not decide within the 4-s limit after the dice cup had started to shake, this trial was counted as a skip. In this case, "Failure – no selection" appeared on the screen. After each decision or non-selection the feedback (the amount of the gain/loss or the failure message) was given for 4 s before the next trial started immediately. This time interval corresponds to the average processing time reported in previous studies with the GDT. The time limit was set to ensure that all tasks were of equal duration, as mentioned above. In contrast to the original version of the GDT, it was possible to skip a trial in the current version if the participant did not indicate a decision on the keypad within 4 s. Therefore, the number of played rounds may differ between participants.

The second experimental condition was an fMRI version of the GDT with a parallel 2-back task (see Figure 11). The goal of this condition was to perform as well as possible in each task and equally well on both tasks.

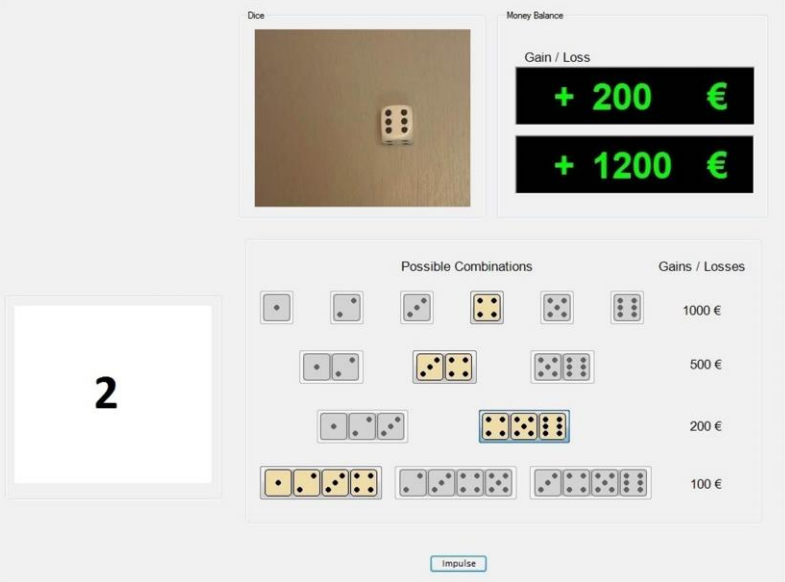

Figure 11 The GDT plus 2-back task modified for fMRI.

On the right side of the screen, participants had to work on the GDT by betting which number will be thrown. They had to select one of the four highlighted possible combinations (one number, combination of two, three, or four numbers) with a four-touch key pad in the right hand. Afterward a die was thrown, followed by the feedback if the participants had won or lost. On the left side of the GDT interface, participants continuously had to monitor the numbers presented. Here, they had to indicate on a keypad in the left hand whether the current number presented was already seen two trials before. For the single-task condition, either the right or left side of the screen was fixed. Thus, participants could only perform the GDT or the 2-back task by itself.

The administered 2-back task was comparable to the high-load parallel executive task used by Starcke and colleagues (2011). Here, participants were asked to monitor the identities of numbers between 0 and 9. The numbers were presented in a pseudorandom sequence, and participants were asked to indicate with the keypad in the left hand whether or not the currently presented number was identical to the number presented two trials before. The stimuli were displayed for 500 ms with an interstimulus interval of 2,750 ms. Thus, participants had a time limit of 500 ms for making their response. The target stimuli (same stimulus as two trials before) were presented randomly with a probability of 33 % (c.f. Schoofs, et al., 2008).

In the third experimental condition, participants had to work on the 2-back task alone.

4.3.6 Procedure and analyses

4.3.6.1 Procedure

The procedure was identical for the SG and the CG with one exception: The SG received the TSST (Clemens Kirschbaum, et al., 1993) for stress inducement, whereas the CG received the placebo TSST (Het, et al., 2009). After the participants had given written informed consent for the experiment, the practice part began. For each experimental condition, the participants received detailed instructions on the screen, followed by a short practice sequence for each task. The GDT was practiced alone for three trials and the 2-back task alone for 20 trials. For the GDT with parallel 2-back task, the GDT was practiced for three trials in parallel with the 2-back task for seven trials. Afterward, the PANAS was completed, and the first salivary sample (baseline) was taken. Subsequently, participants were brought to the room where the TSST or the placebo TSST took place, after that participants were asked to fill in the self-report again, and the second salivary sample was taken (+20 min). Next, participants were brought to the scanner room, and after a third salivary sample (+30 min), the fMRI procedure began. After the fMRI scanning (which in total lasted about an hour, including the experimental design plus shimming, anatomical scans, and preparation time), participants were asked to complete the PANAS and to give a fourth salivary sample (+95 min). The fifth salivary sample was taken during the debriefing (+105 min).

4.3.6.2 Functional magnetic resonance imaging (fMRI) acquisition

Functional MRI scanning was performed with a 7T whole-body MRI system (Magnetom 7T, Siemens Healthcare, Erlangen, Germany) at the Erwin L. Hahn Institute for MRI, Essen, Germany. For this experiment, the scanner was equipped with a 32-channel transmit/receive head coil (Nova Medical, Wilmington, USA).

Before the acquisition of the sequences, B0 shimming was performed using a vendor-provided gradient-echo sequence and an algorithm based on the work of Schär, Kozerke, Fischer, and Boesiger (2004). For B1 field mapping and local flip angle optimization, a vendor-provided spin-echo type sequence was used. After a slice selective excitation, two refocusing pulses generated a spin-echo and a stimulated echo, respectively. The algorithm was mainly based on the work of Hoult (2000). Structural images (0.7 x 0.7 x 0.7 mm^3) were acquired using a modified T1-weighted three-dimensional magnetization-prepared rapid gradient-echo (MPRAGE) sequence: repetition time (TR) = 2500 ms, echo time (TE) = 1.54 ms, field of view (FOV) = 270 x 237 mm^2, flip angle = 7° (c.f. Wrede et al., 2012). Whole functional MRI images were acquired with an optimized bold contrast-sensitive echo-planar-imaging sequence (c.f. Poser, Koopmans, Witzel, Wald, & Barth, 2010). For fMRI, two sessions, each lasting approximately 14 min, were conducted, which led to 790 mosaic

images in total. Each mosaic image contains 144 images (mosaic 12 x 12). The following scan parameters were used: TR = 1,980 ms, TE = 22 ms, FOV = 256 x 253 mm, flip angle = 14°, 144 slices with a voxel size of 1.5 x 1.5 x 1.5 mm^3, Grappa R = 9 (see section 4.3.4.1 for a detailed description of the physical principles of fMRI).

4.3.6.3 Image analysis

Functional images were analyzed using MATLAB (The MathWorks, Inc) and statistical parametric mapping (SPM8, Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm) for all imaging, pre-processing, and voxel-based statistical analyses within the context of the GLM (for a detailed description of functional data analysis see section 4.3.4.2). For movement correction, realignment was assessed using the default SPM8 algorithm, followed by spatial normalization to reduce anatomical differences. Therefore, a standard stereotactic space of SPM8 that means, the Montreal Neurological Institute (MNI) brain and the default SPM8 settings for normalization, was used. To improve the signal and anatomical conformity, spatial smoothing was performed using a Gaussian kernel (5 mm full width at half-maximum). Based on prior hypotheses, we conducted region of interest (ROI) analyses in the PFC, in particular in the dlPFC (Brodmann areas [BA] 9, 10, and 46), in the ACC (BA 24 and 32), and in the parietal cortex (BA 5 and 7). ROIs were defined using WFUPickatlas version 3.0.3 (Maldjian, Laurienti, & Burdette, 2004; Maldjian, Laurienti, Kraft, & Burdette, 2003).

GLMs were applied to the time course of activation, where stimulus onsets were modeled as single-impulse response functions. Linear contrasts of parameter estimates were defined to test specific effects. The resulting statistical maps were entered into second-level *t* test random-effects group analyses. These analyses were conducted to identify significant differences between BOLD (Ogawa, et al., 1990; see also section 4.3.4.1) responses for the planned linear contrasts between the SG and the CG. All effects were reported with a height threshold of $p \leq .001$, uncorrected with an extent threshold of $k \geq 10$ voxel as done in many previous studies (e.g., Ernst et al., 2004; Forstmann, et al., 2006; Hsu, Bhatt, Adolphs, Tranel, & Camerer, 2005; Kukolja, Thiel, Wolf, & Fink, 2008; Otsuka, Osaka, Morishita, Kondo, & Osaka, 2006; Van Snellenberg, Whitman, McDonald, & Liotti, 2007; Yarkoni, Braver, Gray, & Green, 2005). To obtain the associated anatomical structures of the maximum activation, the MNI coordinates of this activity were transformed into Talairach and Tournoux space (Talairach & Tournoux, 1988) using the correction procedure of Brett (1999). Subsequently, the transformed coordinates were put into the Talairach Daemon (Lancaster, Summerln, Rainey, Freitas, & Fox, 1997; Lancaster et al., 2000) to identify the anatomical structures.

4.3.6.4 Statistical analyses of the behavioral data

Statistical analyses of the behavioral data were carried out using the IBM SPSS Statistics software for Windows (Release 19.0; April 18, 2011; SPSS Inc. IBM, Chicago). Potential differences in gender distribution and the distribution of experimental starting time between groups were calculated using Pearson's χ^2 test. To compare the performance in the GDT, the 2-back task, and the GDT plus 2-back task between groups, *t* tests for independent samples as well as one-way analysis of variance (ANOVA) were used. For the stress response analyses, a between-within-subject ANOVA and an ANOVA with repeated measures were used. In case of a violation of the assumption of sphericity (Maulchy's test: $p < .05$), the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. If necessary, Bonferroni correction was applied to adjust α for

multiple comparisons. Simple effect tests were conducted in order to follow up possible main effects and interactions between task performances, affect, and cortisol concentration at different points in time. In order to analyze the relationship between increase in cortisol concentration and brain activation, Pearson's correlations were calculated.

4.4 Results

4.4.1 Stress response

4.4.1.1 Cortisol response to stress

As mentioned above, saliva was collected at five points in time. The +30 min point (before the beginning of the fMRI session) had to be excluded from further analyses because there was not enough saliva to analyze the cortisol concentration in eight samples, most likely because this salivary sample had only been taken about 10 min after the previous sample. At first, it was calculated whether there was an interaction between starting time (pm vs. am) and cortisol concentration for the four points in time (baseline, +20 min, +95 min, and +105 min) using a between- and within-subject ANOVA. The analysis revealed no significant main effect for the between-factor starting time, F (1, 31) = 1.38, p = .249, η^2 = .04, but a significant main effect for the within-factor time, *Greenhouse-Geisser* F (2.30, 71.34) = 6.78, $p \leq .001$, η^2 = .18. The interaction between starting time and time of measurement was also not significant, *Greenhouse-Geisser* F (2.30, 71.34) = 2.44, p = .087, η^2 = .07. Subsequently, a 4 (time) x 2 (group) repeated-measures ANOVA was computed with time as within-factor (baseline, +20 min, +95 min, +105 min) and group (SG vs. CG) as between-factor. The analysis revealed a significant main effect of group, F (1, 31) = 14.03, $p \leq .001$, η^2 = .31, a significant main effect of time, *Greenhouse-Geisser* F (1.78, 55.23) = 8.85, $p \leq .001$, η^2 = .22, and a significant interaction between time and group, *Greenhouse-Geisser* F (1.78, 55.23) = 10.52, $p \leq .001$, η^2 = .25. Further analyses revealed that at baseline the cortisol concentration did not differ between groups, t (31) = 0.52, p = .604, d = 0.18, but at all following points in time, the SG showed higher cortisol than the CG (directly after TSST: t (22.77) = 4.76, $p \leq .001$, d = 1.67; +95 min: t (18.21) = 5.05, $p \leq .001$, d = 1.78; +105 min: t (31) = 2.44, p = .021, d = 0.84).

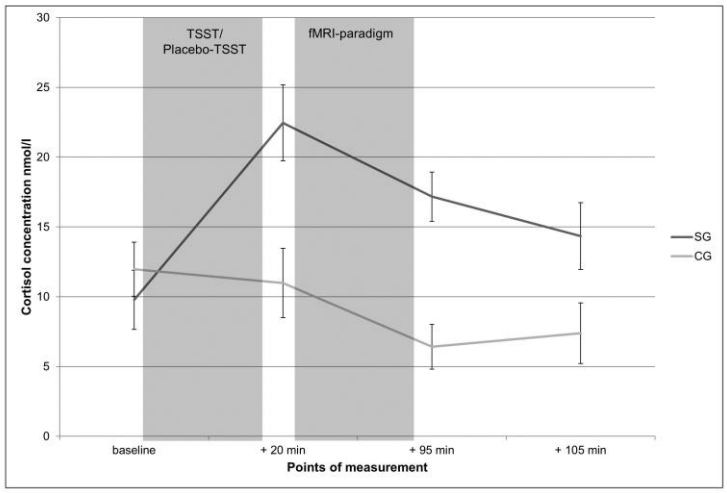

Figure 12 Mean salivary cortisol as a function of time for the stress group (SG) and the control group (CG).

The SG demonstrated a significantly higher cortisol concentration than the CG after the stress induction. The gray bars illustrate the points in time when the stress induction (TSST/placebo TSST) and the fMRI session took place. Note that the fMRI session including the behavioral tasks was during the high cortisol period of the SG. The error bars represent standard deviations.

In total, the SG had a significantly higher cortisol concentration after the TSST (+20 min) and throughout the fMRI paradigm than the CG. These results are summarized in Figure 12.

4.4.1.2 Affect

A 3 (time) *x* 2 (group) repeated-measures ANOVA with time as a within-factor (before the TSST, directly after the TSST, and at the end of the fMRI session) and group as a between-factor (SG vs. CG) was performed separately for the positive and negative affect scales of the PANAS. For the positive affect, the main factor group did not reach significance, F (1, 31) = 0.13, p = .725, η^2 = .01. However, the main factor time was significant, F (2, 62) = 38.94, $p \leq .001$, η^2 = .56. The interaction between group and time was again not significant, F (2, 62) = 0.77, p = .469, η^2 = .02. Post-hoc pairwise Bonferroni-corrected comparisons revealed that participants had a less positive affect at the end of the fMRI session, M = 23.91, SD = 7.21, than before the TSST, M = 31.76, SD = 5.79; $p \leq .001$, d = 1.25, or directly after the TSST, M = 31.39, SD = 6.11; $p \leq .001$, d = 1.21. However, the positive affect did not differ between the points of measurement before the TSST and directly after the TSST, $p > .900$, d = 0.08. For the negative affect, neither main factor group, F (1, 31) = 0.01, p = .930, $\eta^2 \leq .01$, or time, F (2, 62) = 0.46, p = .633, η^2 = .02, nor the interaction between time and group, F (2, 62) = 2.02, p = .141, η^2 = .06, was significant.

In total, there were no significant differences in the self-reported affect between SG and CG (see Table 4).

Table 4 Means and standard deviation of the PANAS at the three points of measurement.

Points of measurement	**Stress group** ***M* (*SD*)**	**Control group** ***M* (*SD*)**
Positive affect scale		
Before the TSST (baseline)	32.00 (5.79)	31.53 (5.97)
Directly after the TSST (+20 min)	31.13 (5.81)	31.65 (6.56)
After the fMRI session (+95 min)	22.88 (7.82)	24.88 (6.68)
Negative affect scale		
Before the TSST (baseline)	13.94 (2.91)	14.12 (2.52)
Directly after the TSST (+20 min)	15.19 (3.89)	13.76 (2.99)
After the fMRI session (+95 min)	13.06 (2.21)	14.53 (4.99)

4.4.2 Behavioral results

Table 5 shows that on a behavioral level, the performance in the GDT, the 2-back task, as well as the GDT plus 2-back task did not differ significantly between the SG and the CG.

Table 5 Comparison of task performance between stress and control group.

Task scores	Stress group *M* (*SD*)	Control group *M* (*SD*)	*t*	*df*	*p*	*d*
GDT						
Rounds	17.81 (0.31)	17.74 (0.50)	0.53	31	.602	0.17
Risky choices in %	33.56 (20.98)	23.58 (20.35)	1.39	31	.175	0.48
2-back task						
Rounds	47.94 (0.25)	47.79 (0.73)	0.75	31	.462	0.27
Correct responses in %	84.13 (15.54)	86.74 (17.03)	0.46	31	.650	0.16
Reaction time[a]	591.13 (111.08)	612.10 (173.58)	0.41	31	.684	0.14
GDT plus 2-back						
GDT: rounds	16.84 (1.21)	17.00 (0.90)	0.42	31	.675	0.15
GDT: risky choices in %	28.75 (24.23)	22.26 (24.78)	0.76	31	.453	0.26
2-back: rounds	47.59 (0.42)	47.44 (1.01)	0.57	21.53	.574	0.18
2-back: correct responses in %	70.62 (12.21)	70.91 (14.42)	0.06	31	.950	0.02
2-back: reaction time[a]	753.42 (238.71)	685.26 (153.02)	0.97	25.30	.341	0.34

[a]In ms.

4.4.3 Imaging data

To investigate the underlying neural correlates of the GDT plus 2-back task, we analyzed the brain areas involved in the dual task compared with the single-task performance (see Table 6 for the CG and Table 7 for the SG). The following contrasts were calculated for each group separately: *GDT plus 2-back > GDT* and *GDT plus 2-back > 2-back* as well as *GDT plus 2-back < GDT* and *GDT plus 2-back < 2-back.*

Table 6 Comparison between dual-task activation and single task activation in the control group.

Contrast	Nearest brain region	Laterality	*k*	MNI - coordinates			Peak	*p*
				x	y	z	*t*	
GDT plus 2back > GDT	Limbic lobe, cingulate gyrus (BA[a] 24)	L	172	-5	-1	49	4.83	≤ .001
		R	172	8	-4	48	4.53	≤ .001
	Frontal lobe, medial frontal gyrus (BA[a] 6)	R	172	6	4	52	3.40	≤ .001
GDT plus 2back < GDT	Occipital lobe, cuneus, (BA[a] 19)	R	15	29	-87	28	4.13	≤ .001
GDT plus 2back > 2-back	Parietal lobe, inferior parietal lobule (BA[a] 40)	R	47	38	-55	58	4.38	≤ .001
	Parietal lobe, superior parietal lobule (BA[a] 7)	L	29	-26	-52	60	4.20	≤ .001
	Parietal lobe, precuneus (BA[a] 7)	R	56	9	-52	55	4.13	≤ .001
		R	33	18	-60	52	4.11	≤ .001
		R	33	26	-57	52	3.74	≤ .001
GDT plus2-back < 2back	n.s.[b]							

[a]Brodmann Area. [b]No significant neural activation differences in the second-level group analysis.

Concerning the CG, there was significantly more activation in parts of the cingulate gyrus as well as in the medial frontal gyrus during the dual task compared with the GDT. However, there was also a significant decrease in activation in the cuneus during the dual-task condition compared with the GDT. Moreover, when comparing the dual-task condition with the 2-back task condition, there was a significant increase in activation in inferior and superior parietal areas (see Table 6).

Table 7 Comparison between dual-task activation and single task activation in the stress group.

Contrast	Nearest brain region	Laterality	*k*	MNI - coordinates			Peak	*p*
				x	y	z	*t*	
GDT plus 2back > GDT	Frontal lobe, middle frontal gyrus (BA[a] 9)	L	91	-36	34	42	5.09	≤ .001
		L	91	-30	43	40	3.58	≤ .001
	Frontal lobe, paracentral lobule (BA[a] 31)	R	67	9	-34	51	4.53	≤ .001
	Frontal lobe, precentral gyrus (BA[a] 6)	R	13	59	1	36	3.99	≤ .001
	Parietal lobe, superior parietal lobule (BA[a] 7)	R	58	35	-51	63	4.78	≤ .001
		R	52	21	-55	64	4.05	≤ .001
GDT plus 2back < GDT	n.s.[b]							
GDT plus 2back > 2-back	Parietal lobe, postcentral gyrus (BA[a] 2, 5)	R	96	33	-48	63	5.50	≤ .001
		R	96	33	-39	69	4.25	≤ .001
	Parietal lobe, superior parietal gyrus (BA[a] 7)	R	89	14	-72	55	4.15	≤ .001
		R	89	23	-64	58	3.95	≤ .001
		L	12	-20	-72	55	3.84	≤ .001
	Parietal lobe, inferior parietal lobule (BA[a] 40)	L	17	-38	-43	61	4.39	≤ .001
	Frontal lobe, superior frontal gyrus (BAa 8)	R	45	20	49	42	4.62	≤ .001
GDT plus2-back < 2back	n.s.[b]							

[a]Brodmann Area. [b]No significant neural activation differences in the second-level group analysis.

Concerning the SG, the analyses revealed significantly more activation during the dual task compared with the GDT in a part of the dorsolateral prefrontal area (middle frontal gyrus, BA 9), in supplementary motor areas (paracentral lobe and precentral gyrus), as well as in the superior parietal lobe. Compared with the 2-back task, there was an increased activation in superior as well as inferior parietal areas, in parts of the supplementary motor area (postcentral gyrus), and in the superior frontal gyrus (see Table 7).

The main focus lay on the interaction effect between stress, decision making, and additional executive load. Therefore, the contrasts *GDT plus 2-back > GDT* and *GDT plus 2-back > 2-back* were also compared between SG and CG, in order to see whether there was an increase in activation (*SG > CG*) or a decrease in activation (*SG < CG*) due to acute stress (see Table 8). The analyses revealed a significant increase in activation (*SG > CG*) in the superior frontal gyrus as well as in the supplementary motor area (paracentral gyrus; see Figure 13) during the GDT plus 2-back compared with the GDT. All other contrasts did not survive the height and extent threshold.

Table 8 Activation pattern during the dual-task paradigm (comparison: GDT2back > GDT and GDT2back > 2-back), compared between stress group (SG) and control group (CG).

Contrast	Nearest brain region	Laterality	*k*	MNI - coordinates			Peak	*p*
				x	y	z	*t*	
GDT plus 2back > GDT								
SG > CG	Frontal lobe, superior frontal gyrus (BA[a] 10)	L	13	-18	47	28	3.92	≤ .001
	Frontal lobe/parietal lobe, paracentral lobule (BA[a] 5)	R	55	12	-34	51	4.16	≤ .001
SG < CG	n.s.[b]							
GDT plus 2back > 2-back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							

[a]Brodmann Area. [b]No significant neural activation differences in the second-level group analysis.

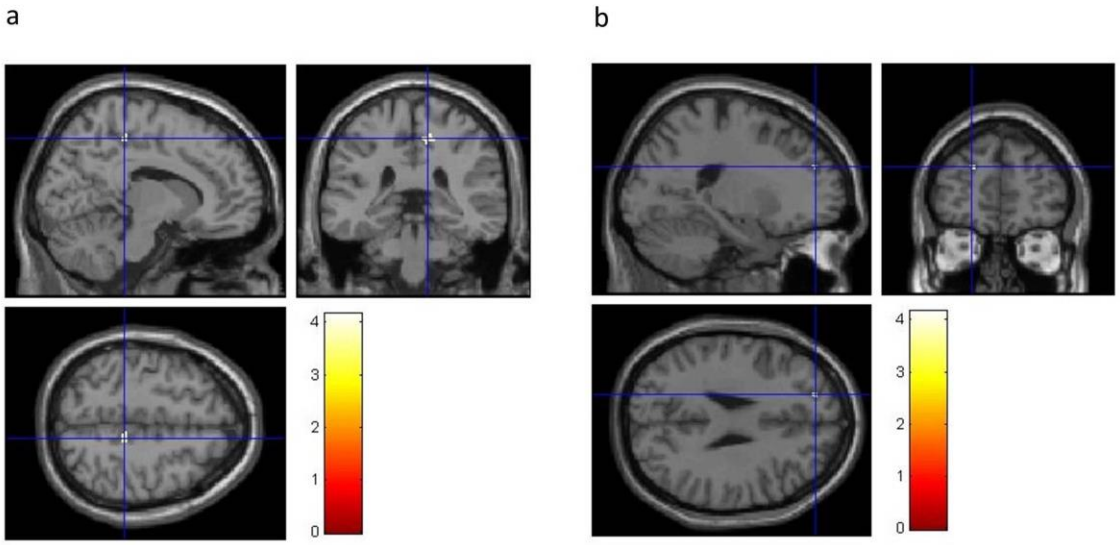

Figure 13 Neural activity underlying the dual-task effect (GDT plus 2-back > GDT) in the stress group compared with the control group.

Results are displayed at a threshold of $p \leq .001$ (uncorrected) and an applied extended threshold of $k \geq 10$ voxel. a) The supplementary motor area (paracentral lobe) and b) the superior frontal gyrus were significantly activated (for detailed information see Table 8).

Additionally, the activation during the GDT solely, the 2-back task solely, and the GDT plus 2-back task was compared between the two groups (see Table 9). Only the comparison concerning the GDT (performed solely) activation survived height and extent threshold, revealing an increase in activation in the superior frontal gyrus during acute stress. Additionally, the precuneus was less activated during acute stress compared with the control condition.

In total, the results demonstrated increased brain activation during the dual task when compared with the single-task performance. However, depending on the single task with which the dual-task performance is compared and depending on the group, different brain areas seem to be involved. Moreover, in the CG there was also a significantly decreased activation in the cuneus during the GDT plus 2-back task compared with the GDT when performed solely. The analysis of the interaction between decision making, executive functions, and stress revealed the following: Stressed participants performing a decision-making task simultaneously with an

executive task show an increased activation in the supplementary motor area and the aPFC (superior frontal gyrus, BA 10) in comparison with stressed participants performing only the decision-making task.

Table 9 Comparison of the activation pattern of each task between the stress group (SG) and the control group (CG).

Contrast	Nearest brain region	Laterality	*k*	MNI - coordinates			Peak	*p*
				x	y	z	*t*	
GDT								
SG > CG	Frontal lobe, superior frontal gyrus (BA[a] 9)	R	23	30	52	33	4.28	≤ .001
SG < CG	Parietal lobe, precuneus (BA[a] 7)	R	13	27	-67	36	4.29	≤ .001
2-back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							
GDT plus 2back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							

[a]Brodmann Area. [b]No significant neural activation differences in the second-level group analysis.

4.4.3.1 Correlations between cortisol concentration and brain activity

In order to analyze the relationship between cortisol concentration and brain activity, we calculated correlations between cortisol data and activations in the ROI for each group.

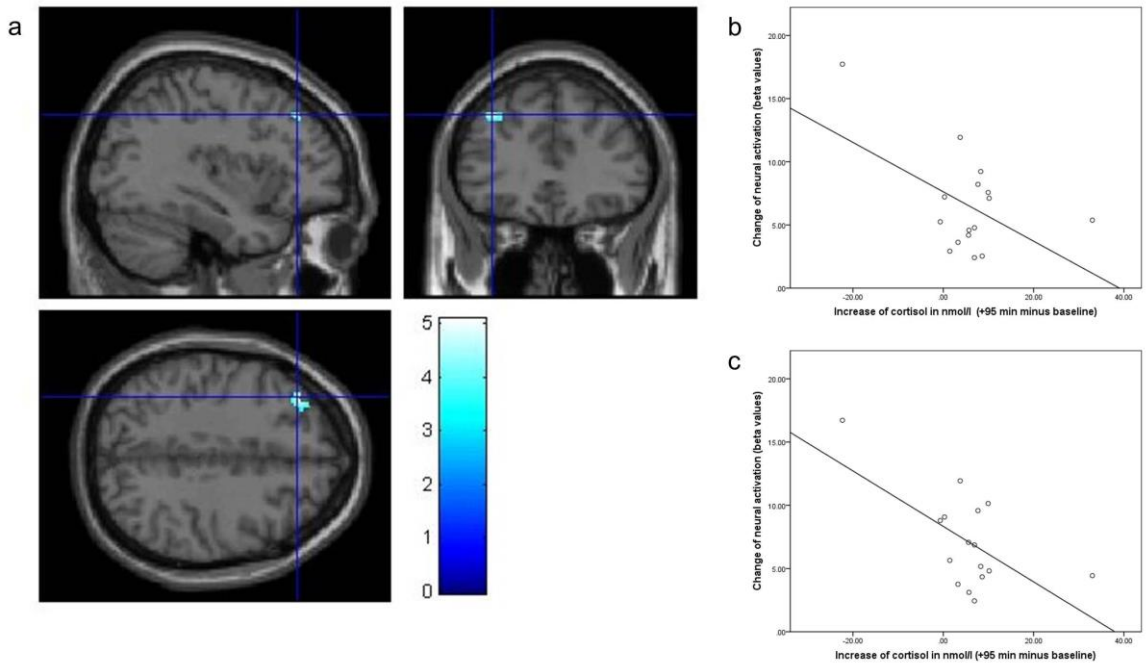

Figure 14 Results of the correlations between cortisol concentration and brain activity.

a) Increasing cortisol concentration in the stress group is associated with a deactivation in the middle frontal gyrus during the GDT plus 2-back when compared with the GDT. The fixing cross was set at MNI-coordinate 1 (x = -36, y = 34, z = 42). The plot of the negative correlation between increase in cortisol in the stress group (from baseline to time point +95 min) and brain activation b) at the MNI-coordinate 1 and c) at the MNI-coordinate 2 (x = -30, y = 43, z = 40).

We used the results from the second-level analyses shown in Table 6 and Table 7. We extracted the parameter estimates (beta values) from each location of the activation pattern resulting from the calculated contrasts for each participant. We also calculated the cortisol increase between baseline and +95 min point of time (directly after the fMRI session) for each participant (cortisol concentration at the +95 min point minus cortisol concentration at baseline). These cortisol data were then correlated with the parameter estimates of the ROI for both groups separately. Results demonstrated a negative correlation between increases in cortisol in the SG and the activation in the left middle frontal gyrus (MNI-coordinate 1: x = -36, y = 34, z = 42; MNI-coordinate 2: x = -30, y = 43, z = 49) for both coordinates (MNI-coordinate 1: r = -.523, p = .038; MNI-coordinate 2: r = -.618, p = .011) in the contrast GDT plus 2-back > GDT. This indicates that an increase in cortisol in the SG is accompanied by less activation of parts of the dorsolateral prefrontal area (i.e., BA 9) during the GDT plus 2-back compared with the GDT (see Figure 14). No other correlations calculated for the SG or CG reached significance.

4.5 Discussion

Overall, stress induction was successful. Stressed participants had a higher cortisol concentration after stress induction and throughout the experiment compared with control participants. The main results support the findings of Pabst, Schoofs, and colleagues (2013) that on a behavioral level acute stress in combination with a parallel executive task do not impair decision-making performance (for a detailed description of these findings see section 3.4.4). More interestingly, the analyses of the neural correlates revealed significant differences between SG and CG: When stressed participants (compared with non-stressed participants) had to make a decision while simultaneously working memory was demanded, a greater activation in BA 10 - the more anterior part of the dlPFC, which is also referred to as the aPFC (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999; Koechlin & Hyafil, 2007) - and in a part of the supplementary motor area (paracentral lobe) was revealed in comparison with the activation when no additional demand was given. Additionally, we found that in the SG the increase in cortisol concentration was negatively correlated with the increase in activation in the BA 9 (the more dorsal part of the dlPFC) regarding the contrast *GDT plus 2-back > GDT*. This indicates that in the SG an increase in stress level is associated with a decrease in neural activation in the dorsal part of the dlPFC during the GDT plus 2-back task compared with the GDT. According to Koechling and Hyafil (2007), the aPFC (BA 10) forms with other prefrontal regions the apex of the executive system whereby it is particularly associated with parallel processing of two tasks. In contrast, BA 9 was found to work more serially upon cognitive processes (Dux, et al., 2006). Based on their neurocomputational model, Koechling and Hyafil (2007) suggested that the aPFC overcomes such serial constraints by joint consideration of two task sets. Plessow and colleagues (2012) and Pabst, Schoofs, and colleagues (2013) assumed that stress may trigger the serial-to-parallel shift by reducing task shielding in order to enable the more resource-efficient parallel processing mode in dual-task situations. The increased activation of the aPFC in the stressed and not in non-stressed participants may be associated with such a serial-to-parallel shift. It may be possible that due to reduced task shielding, the aPFC maintains previously selected task sets in a pending state for automatic retrieval and implementation upon the process of the ongoing task as described by Koechlin and Hyafil (2007). Even though we did not find a deactivation in serially working brain areas (e.g., BA 9; Dux, et al., 2006) in the SG when compared with the CG, the negative relationship within the SG between brain activation in BA 9 and cortisol concentration may

point in the same direction: In decision-making situations with a simultaneous executive task, stress seems to lead to reduced activation of serial processing brain areas (dorsal part of the dlPFC, BA 9) while simultaneously to an increased activation of brain areas associated with parallel processing (aPFC, BA 10). This may have led to a reduced task shielding of the decision-making task as well as the executive task, resulting in good behavioral performance in both tasks. The finding of the increased activation in the supplementary motor area may be most likely due to the fact that performing a single task involved one hand and the participants had to give their answers only every 4 s. In contrast, when performing both tasks (GDT plus 2-back) simultaneously, participants had to use their second hand and give an answer at least every 2,750 ms. This might have led to a greater motor and sensory response. However, it has to be mentioned that this increased activity was only found in the SG and not in the CG. Therefore, we assume that this increase may also be due to the serial-to-parallel shift in the SG: Performing two tasks serially is probably accompanied by less motor response because only one hand at a time needs to be used. In contrast, performing two tasks simultaneously involves both hands, probably leading to an increased motor response.

Studies investigating reactivity of stress in the brain found that stress increases the release of catecholamine, in particular dopamine (Abercrombie, Keefe, DiFrischia, & Zigmond, 1989; Hutson, Patel, Jay, & Barton, 2004; Morrow, Roth, & Elsworth, 2000). Since the PFC provides a high density of D1 receptors, the influence of stress leads to a high activity in this area (Thierry, Tassin, Blanc, & Glowinski, 1976; Williams & Castner, 2006). However, most studies found that an increase in dopamine is followed by an impairment of cognitive functions (Arnsten, 2009; Arnsten & Goldman-Rakic, 1998), which was not found in the current study. Here, stressed participants performed all tasks as well as the CG in both executive associated tasks. Regarding the GDT plus 2-back task performance, the current finding seems to be in line with a recent study also demonstrating that stress does not impair dual-tasking performance (Beste, Yildiz, Meissner, & Wolf, 2013) and may be due to a shift to a less demanding processing mode (c.f. Pabst, Schoofs, et al., 2013; Plessow, et al., 2012; see also section 3.4.4). Still, this cannot explain the missing differences in the single-task conditions. In particular, decision-making performance as well as working memory performance was found to be reduced by stress (e.g., Lupien, Gillin, & Hauger, 1999; Porcelli & Delgado, 2009; Putman, Hermans, & van Honk, 2010; Schoofs, et al., 2008; Starcke, et al., 2008). Possible explanations why we did not find any differences in task performance are briefly discussed in section 4.5.1.

Regarding the single-task performance, the analyses of the neural correlates revealed again significant differences between the SG and the CG but only during the GDT: Stressed participants showed increased activation in the dorsal part of the superior frontal gyrus (dlPFC) and decreased activation in the precuneus. Both areas are known to be involved in decision making under risk (Labudda, et al., 2008; Lighthall, et al., 2012; see also section 3.3): The dorsal superior frontal gyrus is part of the dlPFC and therefore involved in executive functioning (Alvarez & Emory, 2006; Lie, et al., 2006; see also section 3.2.1), while the precuneus is especially associated with mental arithmetic (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Stanescu-Cosson et al., 2000). Both regions are highly relevant for GDT performance (Labudda, et al., 2008). However, the current findings may suggest that under stress, brain areas associated with executive functions seem to be more involved than areas associated with mental arithmetic. This may be because executive functions are involved in task shielding, which is known to be increased in demanding single-task situations in order to perform well on the task (Plessow, et al., 2011).

All other comparisons of the neural correlates between SG and CG (GDT plus 2-back solely, 2-back solely, and GDT plus 2-back > 2-back) revealed no significant differences. Concerning the 2-back task solely, the results are in contrast to those reported by Cousijn and colleagues (2012) and Qin et al. (2009) who found decreased activation in different brain areas due to acute stress while performing an n-back working memory task. However, it has to be mentioned that the areas that were deactivated in those studies are different: While Cousijn and colleagues (2012) found a decrease in activation in the medial temporal lobe in male participants, Qin et al. (2009) found a deactivation in the dlPFC in female participants. Thus, the findings reveal no homogeneous picture. Additionally, the stressor in the current study (TSST) differed completely from the one used in the other two studies (aversive movie clips). This may have led to differential stress reactions resulting in the heterogeneous findings. It may be advisable to engage in further research in order to get a clearer picture of the activation pattern when performing a 2-back task under the influence of acute stress (e.g., using similar stressors or directly comparing the differential stress reactions due to different stressors).

So far and to our best knowledge, this is the first study that investigated the underlying neural correlates of the GDT plus 2-back task. Therefore, we additionally compared the activation patterns of the dual task with the decision-making task (GDT plus 2-back > GDT) within the CG only. This revealed an increased activity in the cingulate gyrus as well as in the medial frontal gyrus. These areas were also found to be activated in studies investigating neural correlates during working memory (for a review see Owen, et al., 2005). While the activation in the medial frontal gyrus is additionally associated with executive functioning (Talati & Hirsch, 2005), the activation in the anterior part of the cingulate gyrus emphasizes the increased complexity and effort in the dual task (Callicott et al., 1999). The resulting activation pattern when comparing the dual task with the 2-back task (GDT plus 2-back > 2-back) is in line with the study by Labudda and colleagues (2008), which investigated the neural correlates of decision making using a paradigm similar to the GDT. The activated brain areas are associated with number processing, exact calculation (inferior parietal lobe; Dehaene, Molko, Cohen, & Wilson, 2004; Pesenti, Thioux, Seron, & De Volder, 2000) and mathematical approximation functions (precuneus, superior parietal lobe; Dehaene, et al., 1999; Stanescu-Cosson, et al., 2000), which are involved in the GDT performance. Those comparisons reveal that the manipulation of the dual task as well as each single task was successful and support the validity of our findings discussed above.

4.5.1 Limitations

There are some limitations to our study, which have to be mentioned. First, the fMRI version of the GDT was most likely easier to perform than the original version, since participants only had to choose among four instead of 14 alternatives. This could be the reason why we did not find significant differences on a behavioral level. Secondly, the experimental conditions (GDT, 2-back, and GDT plus 2-back) and the high-level control task were all similar in design and visual input. Therefore, it may be possible that even though the participants were advised to perform one of the single tasks (GDT or 2-back), they still paid attention to the second task on the screen, even though it was frozen and not executable. This circumstance was not controlled, and given that we had a within-subject design with respect to the different activation conditions (GDT solely, 2-back solely, and GDT plus 2-back), this may have reduced the power for the comparison between the SG and CG in the second-level analyses. In future studies, it would be helpful to use the activation conditions as a between-factor, as well. Thirdly, the time interval after the TSST until the end of the behavioral tasks, in which we investigated the

influence of stress, was around 60 min. However, it is known that the peak cortisol response is about 21 to 40 min after the onset of a stressor (Dickerson & Kemeny, 2004) and should return to baseline 41 to 60 min after cessation of the stressor (Clemens Kirschbaum & Hellhammer, 1994). Nevertheless, the data demonstrated that the SG compared to the CG had a higher cortisol concentration after the TSST as well as at the end of the study. Fourthly, the fMRI investigation itself was an unfamiliar situation for the participants, in which they were confronted with loud noises from the scanner and other unfamiliar conditions that could have created stress in the participants (c.f. Eatough, Shirtcliff, Hanson, & Pollak, 2009; Tessner, Walker, Hochman, & Hamann, 2006). This could have had a reducing effect on the positive affect in all participants, and therefore, group differences in the PANAS might have been diminished, resulting in a non-significant group effect on the subjective stress response. Still, as mentioned before, the physiological data (cortisol concentration) demonstrated that the neuroendocrine stress level differed between groups: The SG had a higher cortisol concentration than the CG. Therefore, we concluded that the stress induction was successful. However, in future studies it might be helpful to further reduce the subjective stress level in the CG and to increase the stress level in the experimental group to have stronger effects on both behavioral and neural level. Finally, it has to be pointed out that the assumptions regarding the serial-to-parallel shift need to be treated with caution. Due to the fact that the contrast GDT plus 2-back > 2-back did not reveal any significant results, it may be possible that the current findings regarding the contrast GDT plus 2-back > GDT are task specific. Additionally, the activation found in this contrast is of very small cluster size (k = 13).

4.5.2 Conclusion

Despite these limitations, we conclude that the findings reported here support the results of Pabst, Schoofs, and colleagues (2013) that acute psychological stress in combination with a parallel executive task seems to preserve decision-making performance from decreasing. Moreover, the current study reveals that making advantageous decisions in a stressful situation, while simultaneously working memory is demanded otherwise, is accompanied by an increased activation in the aPFC (BA 10). Thus, this region may be included in the process that maintains good decision-making performance. Pabst, Schoofs, and colleagues (2013) assumed that such underlying mechanism may be a shift from sophisticated serial processing mode to a less demanding parallel processing mode (Plessow, et al., 2012). It may be possible that the aPFC is involved in this mechanism, because it was found that this region overcomes the serial constraint of two tasks by joint consideration of those, resulting in a parallel processing mode (Koechlin & Hyafil, 2007). Future studies should investigate the possible role of the aPFC in the serial-to-parallel shift in more detail. Several studies demonstrated that patients with executive dysfunctions have problems performing two tasks simultaneously (Baddeley, et al., 1997; Dalrymple-Alford, et al., 1994; Greene, et al., 1995). Understanding the neural and cognitive mechanisms in dual tasking in more detail may give us the opportunity to further investigate how it may be possible to train or compensate those functions so that in case of executive dysfunctions or in demanding situations, the handling of two task simultaneously will still be manageable.

5. Study 2: Performing a secondary executive task with affective stimuli interferes with decision making under risk conditions

5.1 Abstract

Previous studies demonstrated that executive functions are crucial for advantageous decision making under risk and that therefore decision making is disrupted when working memory capacity is demanded while working on a decision task. While some studies also showed that affective influences have an effect on decision making under risk, it is unclear how affective processing and executive functions predict decision-making performance in interaction. The current experimental study used a between-subjects design to examine whether affective pictures (positive and negative pictures compared to neutral pictures), included in a parallel executive task (working memory 2-back task), have an impact on decision making under risk as assessed by the GDT. Moreover, performance GDT plus 2-back task was compared to performance in the GDT without any additional task (GDT solely). The results show that performance in the GDT differed between groups (positive, negative, neutral, and GDT solely). The groups with affective pictures, especially those with positive pictures in the 2-back task, showed more disadvantageous decisions in the GDT than the groups with neutral pictures and the group performing the GDT without any additional task. However, executive functions moderated the effect of the affective pictures. Regardless of affective influence, subjects with good executive functions performed advantageously in the GDT. These findings support the assumption that executive functions and affective processing interact in predicting decision making under risk.

5.2 Introduction

Decision making is an important key function in everyday life. Therefore, a huge number of studies addressed decision making under certain conditions, for example, risk (see e.g., sections: 3.1.2.2, 3.2.2.2, 3.4.1.4.2, 3.4.2.2.2, and 3.4.3.3.2). That executive functions have an important role in decisions under risk became obvious in chapter 3.2. Furthermore, Starcke and colleagues (2011) demonstrated that when performing an additional executive task in parallel with a decision-making task (GDT), leads to inferior decision-making performance. Thus, the authors assumed that the GDT taps into system 2 (Kahneman, 2003; for more detail about the study see section 3.4.1.4.2). This again emphasized the crucial role of executive functions (and therefore aspects of system 2) for advantageous decision making under risk. These findings received support from several fMRI-studies (for detailed information about fMRI see section 4.3.4) showing activations in the dlPFC while making decisions under risk, an area also known to be involved in executive functioning (for more information about neural correlates of decision making and executive functions see section 3.3 and 3.2.1). Additionally, these results are in accordance with a model of decision making under risk (Brand, et al., 2006; see also section 3). As mentioned in section 3 it is assumed that in decisions under risk cognitive as well as affective processes are involved. Brand and colleagues (2006) argued that decisions under risk can principally be made using cognitive processes alone that means that affective reactions to feedback are not necessarily involved. However, the authors also proposed that the combination of cognitive and affective components will lead to the best performance in the decision-making process under risk. In the past few years, several studies using the GDT provided further support for this model. For example, it has been demonstrated that besides processing the (affective) feedback of previous decisions (Brand, 2008), individuals benefit from the application

of analytical strategies (Brand, Heinze, et al., 2008). Moreover, the necessity of receiving feedback to perform well on the task is moderated by the individuals' executive functioning (Brand, Laier, et al., 2009): Subjects with relatively low executive functions do need feedback to perform well, while participants with superior executive functions perform advantageously with and without feedback (for more information see sections 3.1.2.2, 3.2.2.2, 3.4.1.4.2, 3.4.2.2.2, and 3.4.3.3.2.) In summary, it seems that the affective and the cognitive way play an important role in decision making under risk, but it is still unclear whether or not the interaction between both systems may influence the decision-making performance.

Different studies showed that processing affective stimuli interfere with executive functioning (Dolcos, Diaz-Granados, Wang, & McCarthy, 2008; Dolcos & McCarthy, 2006; Kensinger & Corkin, 2003; Perlstein, et al., 2002). In their fMRI-study, Dolcos and McCarthy (2006) as well as Dolcos and colleagues (2008) demonstrated that affective stimuli distract participants and lead to reduced working memory performance at least on individual levels. During performance activation in the dlPFC was found that decreased when affective stimuli were presented while the activity in the ventral brain area (e.g., the amygdala) increased simultaneously. The authors suggested that this deactivation in the dlPFC led to diminished cognitive performance. These findings correspond with Perlstein and colleagues (2002) who showed that unpleasant stimuli in a working memory task lead to reduced activation in the dlPFC when compared to pleasant or neutral stimuli that in turn leads to weaker working memory performance. Similarly, Kensinger and Corkin (2003) demonstrated that in a n-back task with sad and neutral faces, participants responded more slowly to sad faces than to neutral faces. Given these results and the findings concerning (affective) feedback-processing (Brand, 2008; Brand, Laier, et al., 2009), the question remains whether an additional load of the executive system as well as a simultaneous load on the affective system would lead to an even stronger impairment of decision-making behavior. In the current study it is assumed that simultaneous performance of a decision-making task and a parallel executive task involving affective pictures would reduce both: The resources of the executive system and the resources of the affective feedback processing, which are necessary for effective decision making under risk (Brand, 2008; Brand, Laier, et al., 2009). Therefore, decision-making performance should be worse in the affective than in the neutral or no simultaneous task conditions. However, this may not be the case for all types of affective stimuli. There are studies demonstrating that differential valences of affect (negative and positive) has a different influence on cognitive processes: While some showed that negative and not positive affective stimuli interfere with working memory performance (Kensinger & Corkin, 2003) and lead to risk-averse behavior (Alhakami & Slovic, 1994; Slovic, Finucane, Peters, & MacGregor, 2004), other studies suggested that positive affect reduces executive task performance (Spies, Hesse, & Hummitzsch, 1996) and leads to risk-seeking behavior (e.g., Cheung & Mikels, 2011; Heilman, et al., 2010; Romer & Hennessy, 2007; Yuen & Lee, 2003). Therefore, in the current study affective stimuli of different valence (positive and negative) were used. However, the additional load on executive functioning and the simultaneous demand on the affective system (due to processing of affective stimuli) should lead to a combined negative effect on decision making, independent of the affective valence, because of an interference with both systems (the cognitive and the affective system) involved. The current study investigated this hypothesis. In addition, it was also investigated whether the assumed effects of task interference due to an affective parallel task are moderated by an individuals' level of executive functioning. This was not done in any of the previous studies mentioned. Similar to Starcke and colleagues (2011) a 2-back working memory task as a parallel executive task was used, albeit with affective and neutral

pictures instead of numbers. It is hypothesized that the parallel executive task more strongly interferes with GDT performance when affective (positive or negative) pictures are used, as compared to the effect of neutral ones. Due to the fact that system 2 appears to be the crucial system for decision making under risk (Starcke, et al., 2011) and because several studies showed that executive functions seem to moderate or at least influence the performance in the GDT (Brand, Laier, et al., 2009; Euteneuer, et al., 2009; Schiebener, et al., 2011), it is additionally assumed that this effect should be moderated by the participants' general level of executive functioning: Participants with good executive functions should show improved decision-making performance independently of the affective stimuli in the 2-back task. However, compared to a group that performed the GDT by itself, the decision-making performance in all three groups with a parallel executive task simultaneously to the GDT (positive, negative, and neutral) should be reduced.

5.3 Methods

5.3.1 Participants

A sample of 194 healthy volunteers (mean age: 27.11 years, *SD* = 10.08, range: 18-59, 99 female) was examined. The participants were students of the University of Duisburg-Essen as well as their relatives and friends. Participation was voluntary and participants were not compensated for participation. None of the participants had neurological or psychiatric diseases as determined by a screening interview. All participants in the dual-task conditions in which both hands had to be used to perform the tasks (see description in sections 5.3.2.1 and 5.3.2.2), were right-handed. They were randomly assigned to one of four conditions: GDT with secondary 2-back task including positive stimuli (positive group), GDT with secondary 2-back task including negative stimuli (negative group), GDT with secondary 2-back task including neutral stimuli (neutral group), and a CG with the GDT without a parallel task (GDT solely). Table 10 displays the demographic data of the four groups.

5.3.2 Instruments

5.3.2.1 Decisions under risk: Game of Dice Task (GDT)

In order to measure decision making under risk, the GDT (Brand, Fujiwara, et al., 2005; see also Table 1) was utilized. The goal of this computerized task was to maximize the fictitious starting capital of €1,000. The game consisted of 18 trials in which a virtual die is thrown and the participants were asked to guess which number will be thrown next. During each of the 18 trials, participants were able to bet on one single number and combinations of two, three, or four numbers. The options were permanently shown on the screen. If the chosen number or one number of the chosen number combination was thrown the participants won, otherwise they lost. Each option offered was associated with explicit and stable gains and losses (which are also permanently presented on-screen) and winning probabilities (not shown on-screen): The choice of a single number provided a €1,000 gain/loss (winning probability 1:6), the choice of one of the other combinations provided a €500 gain/loss for two numbers (winning probability 2:6), a €200 gain/loss for three numbers (winning probability 3:6), and a €100 gain/loss for four numbers (winning probability 4:6). For example, if a participant bet on the combination of two numbers such as a "one" and a "two", and a one or a two was thrown, he/she won €500. If one of the other numbers was thrown ("three", "four", "five", or "six") the subject lost €500. Following each

decision the participant received visual feedback about the amount of gain (colored green) or loss (colored red). The current capital and the remaining rounds were also shown on-screen. The different options were categorized into disadvantageous (one number and the combination of two numbers with a winning probability of less than 34 %) and advantageous decisions (combination of three and four numbers with a winning probability of 50 % and higher). The advantageous categories are known to lead to a positive outcome in the long run. Choosing these options all the time statistically led to a positive final balance given the starting capital of €1,000 or more. Therefore, the three-number and four-number options were classified as advantageous or low risk and the one-die and two-dice options as disadvantageous or high risk as mentioned in previous studies (e.g., Bayard, Raffard, & Gely-Nargeot, 2011; Brand, Laier, et al., 2009).

To evaluate performance in the GDT, a net score was calculated by subtracting the number of disadvantageous decisions from the number of advantageous decisions. A positive net score indicated advantageous or low-risk behavior (c.f. Brand, Grabenhorst, et al., 2007; Delazer, et al., 2007; Fond, et al., 2012). Additionally, the frequency of the riskiest choice (one single number) was used for analysis. A high frequency indicated disadvantageous decision making (c.f. Brand, Heinze, et al., 2008; Schiebener, et al., 2012; Starcke, et al., 2011).

5.3.2.2 The parallel executive task: 2-back with pictures

Simultaneously to the GDT and on the same computer screen (embedded into the GDT interface to the left of the GDT, see Figure 15), a parallel working memory 2-back task was performed (similar to Starcke, et al., 2011).

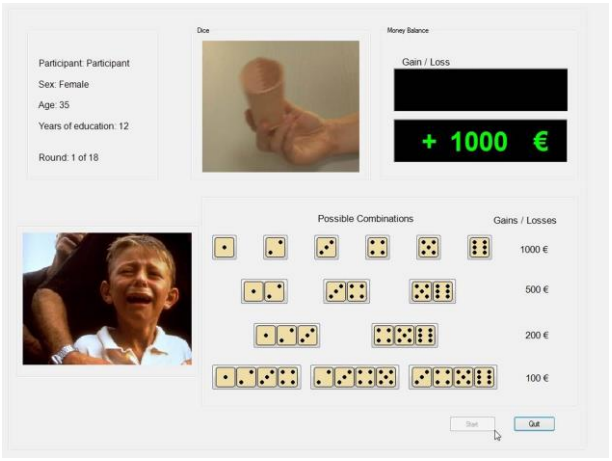

Figure 15 GDT plus 2-back task with negative pictures.

On the right side of the screen, participants have to work on the GDT by betting which number will be thrown. On the left side participants continuously have to monitor the pictures presented (selected from the International Affective Picture System (IAPS); Lang et al., 2008) and have to indicate whether or not the current picture was presented two trials before.

In contrast to the task used by Starcke and colleagues (2011) in which a 2-back task with numbers was used, we used pictures of three different categories as stimuli in the working memory task. In the current version of the 2-back task, participants had to monitor the identity of the pictures. Depending on the condition (group), the pictures were of negative, positive, or neutral valence (selected from the International Affective Picture System (IAPS); Lang, et al., 2008). We selected 10 pictures for each valence. Positive pictures were selected to be relatively high in valence (M = 7.47, SD = 0.33) and arousal (M = 4.96, SD = 0.54), but they did not contain

any erotic scenes. Negative pictures were selected to be relatively low in valence (*M* = 2.57, *SD* = 0.53) and high in arousal (*M* = 5.49, *SD* = .31), and neutral pictures were selected to be relatively low in both valence (*M* = 4.91, *SD* = 0.46) and arousal (*M* = 2.85, *SD* = 0.62). The pictures were presented in a pseudorandom sequence and participants were asked to press one of two keyboard buttons to indicate whether the currently presented picture was identical to the picture presented two trials before or not. The timing parameters were based on Schoofs, Preuss, and Wolf (2008): The stimuli were displayed for 500 ms with an inter-stimulus interval of 2,750 ms. Thus, participants' response time was limited to500 ms. Target stimuli were presented randomly with a probability of 33 % (c.f. Schoofs, et al., 2008).

The performance on the 2-back task was computed as the percentage of correct responses as well as reaction time in ms. While the 2-back task had to be solved with the left hand on the keyboard, the participants were asked to use the mouse with their right hand to execute the GDT.

5.3.2.3 Executive functions: Modified Card Sorting Test (MCST)

The MCST (Nelson, 1976) was used to measure subcomponents of executive functioning such as cognitive flexibility, set-shifting, and categorization as well as the ability to use feedback (see Lezak, et al., 2004; Strauss, et al., 2006). Participants were required to sort a deck of 48 cards according to a certain predetermined rule. The cards were sortable in three ways: by color, number, or shape of the symbols on the cards. The possible sorting rule had to be learned through trial and error using the feedback (right or wrong). The sorting rule changed after six consecutive correct responses and subjects needed to figure out a new sorting rule.

Following variables were used for the analysis of the MCST: the number of categories solved and the number of incorrect responses. Incorrect responses were broken down into perseverative errors, in which the participant continued to sort the cards according to the previous rule, and non-perseverative errors, in which the error was unrelated to the previous sorting rule.

5.3.3 Procedure

Upon arrival, participants were asked to fill out a demographic questionnaire. Next, the MCST was administered followed by the GDT plus 2-back or the original version of the GDT (without parallel 2-back task). Before the dual task started, participants were introduced to both tasks (GDT and 2-back) and each task was practiced separately. Participants were instructed to work on both tasks with equal focus and to perform as good as possible on both tasks. Afterward, the debriefing took place. The entire procedure lasted approximately 30 min.

5.3.4 Statistical analyses

Statistical analyses were carried out using IBM SPSS Statistics software for Windows (Release 19.0; April 18, 2011; SPSS Inc. IBM, Chicago). To compare groups concerning gender, Pearson's χ^2 test was used. The *t* test for independent samples and the One-Way-ANOVA were used to compare the performances in the GDT, the 2-back task, and the MCST between groups. Analyses of covariance (ANCOVA) and correlations were calculated in order to analyze whether possible differences in GDT performance between groups were due to 2-back task performance. If necessary, Bonferroni correction was applied to adjust the Alpha for multiple comparisons. In addition, moderated regressions (J. Cohen, Cohen, Aiken, & West, 2003) were performed to analyze the hypothesized interaction between stimuli-valence and executive functioning in predicting GDT performance.

5.4 Results

Table 10 demonstrates that the groups did not differ regarding gender, age, or executive functions as measured by the MCST. Post-hoc pairwise Bonferroni-corrected comparisons revealed no significant differences between groups for each variable of the MCST, p's $\geq .150$.

Table 10 Between-group comparison of participants' characteristics.

	Groups							
	Negative M (SD)	**Positive M (SD)**	**Neutral M (SD)**	**GDT-solely M (SD)**	***F***	***df1, df2***	***p***	***η²***
n	37	38	37	82				
Sex (female|male)[a]	18|19	20|18	18|19	43|39	0.27[b]	3	.965	
Age	27.95 (12.52)	26.16 (8.87)	25.89 (10.00)	27.72 (9.50)	0.48	3, 190	.701	.01
Executive functions (MCST)								
Categories[c]	5.86 (0.35)	5.58 (1.00)	5.68 (0.58)	5.52 (1.05)	1.40	3, 190	.246	.02
Non-perseverative errors[c]	3.78 (2.51)	4.76 (3.35)	4.73 (2.33)	5.23 (4.25)	1.48	3, 190	.223	.02
Perseverative errors[c]	0.43 (0.65)	1.13 (1.91)	0.97 (1.30)	1.05 (1.36)	2.10	3, 190	.102	.03

[a]Frequency. [b]Chi square. [c]Raw score.

Table 11 shows the average performance in the GDT plus 2-back task or the GDT solely for all groups (negative, positive, neutral, and GDT solely).

5.4.1 Game of Dice Task (GDT): Comparison of the performance of the four groups (negative, positive, neutral, and GDT solely)

Comparing the performance of the GDT across the four groups, an ANOVA with GDT net score as dependent variable and group as between-factor revealed a significant main effect of group (see Table 11). Post-hoc pairwise Bonferroni-corrected comparisons revealed that the positive group had a significant lower net score than the neutral group, $p = .002$, $d = .67$, and the GDT-solely group, $p \leq .001$, $d = .73$. This designates that the participants of the positive group more often chose the disadvantageous/ high-risk options than the neutral and GDT-solely group. Moreover, the difference between the negative group and the GDT-solely group was significant, $p = .033$, $d = .64$, indicating that the negative group chose the disadvantageous/ high-risk options more often than the GDT-solely group. While there was no significant difference between the negative and the positive group, $p = .937$, $d = .25$, as well as between the neutral and the GDT-solely group, $p \geq .99$, $d = .07$, there was a medium effect size (c.f. J. Cohen, 1992) for the difference between the negative group and the neutral group, $d = .55$, but the difference did not reach significance, $p = .185$. This suggests that the participants who processed positive pictures in the 2-back task chose the disadvantageous/high-risk options more often than participants who processed neutral stimuli and those who performed the GDT without additional task. However, there also seems to be at least a trend that the negative group chose the disadvantageous options more often than the neutral group. To ensure that the group differences in the net score were not due to working memory

performance, an additional ANCOVA was calculated using the percentage of correct responses in the 2-back task as covariate. The analysis revealed that the factor group was still significant, $F = 5.25$, $p = .007$, $\eta^2 = .09$. The covariate did not explain a significant part of the variance of the net score, $F = 3.40$, $p = .068$, $\eta^2 = .03$. This suggests that GDT performance in the groups with affective pictures is diminished due to the affective pictures and not because of lower working memory performance.

Table 11 Between-group comparisons (negative, positive, neutral, and GDT-solely) of task performance.

	Groups							
	Negative	**Positive**	**Neutral**	**GDT-solely**				
	M (SD)	**M (SD)**	**M (SD)**	**M (SD)**	***F***	***df1, df2***	***p***	***η²***
GDT								
Net score	10.16 (6.62)	8.05 (10.11)	13.41 (5.01)	13.73 (4.39)	8.37	3, 190	≤. 001	.12
One single number	0.65 (1.27)	2.08 (3.58)	0.41 (0.60)	0.30 (0.60)	9.70	3, 190	≤. 001	.13
2-back task								
Correct responses[a]	74.15 (12.07)	60.38 (21.41)	60.07 (22.24)	-	6.54	2, 109	.002	.11
Reaction time[b]	1,072.92 (285.32)	963.24 (301.89)	1,084.57 (331.60)	-	1.79	2, 109	.171	.03

Note. The comparison of the 2-back task includes only the groups negative, positive, and neutral, because the GDT-solely group performed the original version of the GDT without 2-back task. [a]In percentage. [b]In ms.

When using one single number of the GDT options as dependent variable and group as a between-factor, the main effect of group was significant (see Table 11). Post-hoc pairwise Bonferroni-corrected comparisons showed that participants of the positive group chose the riskiest option of the GDT more often than the neutral group, $p \leq .001$, $d = .65$, the negative group, $p = .003$, $d = .53$, as well as the GDT-solely group, $p \leq .001$, $d = .69$, indicating a difference in choice-behavior between the negative and the positive group. The other group comparisons did not reach significance, p's $\geq .99$, d's $\leq .35$. When controlling for working memory in an ANCOVA (2-back task: Percentage of correct responses) the factor group was still significant, $F = 5.67$, $p = .005$, $\eta^2 = .10$, even though the covariate was significant, $F = 6.29$, $p = .014$, $\eta^2 = .06$. Additional correlation analysis revealed a negative correlation between the 2-back task and the single die option ($r = -.248$, $p = .008$), indicating that good working memory leads to less frequent choices of the riskiest option. Those findings indicate that working memory seems to be involved in GDT performance, but is not responsible for the group differences.

Analysis of the use of feedback in the GDT between groups (see Table 12) revealed significant differences for most feedback scores. Only the comparison regarding the "used feedback after a high-risk choice for a shift to a low-risk option" did not reach significance. Post-hoc pairwise Bonferroni-corrected comparisons demonstrated that compared to the GDT-solely group, participants of the positive group shifted less often to the low-risk option after receiving positive feedback ($p = .032$, $d = .82$), persisted less often on the low-risk options after receiving negative feedback ($p \leq .001$, $d = .81$), and maintained low-risk options less often after receiving positive feedback ($p \leq .001$, $d = .63$). When compared to the neutral group, the positive group persisted less often on the low-risk options after receiving negative feedback ($p = .013$, $d = .56$) and maintained low-risk options less often after receiving positive feedback ($p = .005$, $d = .69$). Moreover, participants of the negative group persisted less often on the low-risk options after receiving negative feedback than participants of the

GDT-solely group (p = .006, d = .76). All other post-hoc pairwise Bonferroni-corrected comparisons did not reach significance.

Table 12 Analyses of the GDT feedback scores.

	Groups							
	Negative M (SD)	**Positive M (SD)**	**Neutral M (SD)**	**GDT-solely M (SD)**	***F***	***df1, df2***	***p***	***η²***
Used negative feedback after a high-risk choice for a shift to a low-risk option[a]	67.09 (23.95) (n = 27)	66.90 (34.81) (n = 27)	81.99 (29.11) (n = 27)	82.03 (32.68) (n = 51)	2.52	3, 128	.061	.06
Used positive feedback after a low-risk choice for maintaining on a low-risk option[a]	78.56 (24.92) (n = 37)	73.89 (29.95) (n = 37)	89.76 (12.18) (n = 37)	88.65 (13.73) (n = 82)	6.59	3, 189	≤ .001	.10
Shifts to a low-risk option after receiving a gain following a high-risk decision[a]	72.83 (39.43) (n = 23)	54.91 (42.62) (n = 19)	84.33 (26.01) (n = 10)	85.40 (30.94) (n = 29)	3.03	3, 77	.035	.11
Persisting on a low-risk option after receiving a loss following a low-risk decision[a]	78.57 (26.83) (n = 37)	72.19 (36.78) (n = 36)	89.29 (24.16) (n = 37)	94.14 (10.71) (n = 82)	8.39	3, 188	≤ .001	.13

Note. In these analyses participants are only included in case they chose the particular option (e.g., low-risk option) and received the specific feedback (e.g., positive feedback) at least once during the game. Thus, the number of participants entered in the analyses differs between variables used. [a]In percentage.

Overall, the results demonstrate that decision-making performance diminishes when participants have to perform a parallel executive task involving affective pictures (of positive or negative valence) simultaneously compared to the decision-making performance when no parallel executive task has to be performed simultaneously. In contrary, participants performing the decision-making task with a parallel executive task with neutral pictures demonstrated no different decision-making performance than the participants performing the decision-making task alone. Moreover, while the difference of the net scores between the positive and neutral group was significant and demonstrated a high effect size, the difference between the negative and the neutral group was not significant, but had a medium effect size. However, the comparison of selecting the riskiest option (one single die) between the negative and neutral group did not reach significance and did not show an effect. The feedback analyses revealed that participants, who were subject to the affective (negative and positive) stimuli in the n-back task, used feedback less often than the neutral or the GDT-solely group.

5.4.2 2-back task: Comparison of the performance of the three groups (negative, positive, and neutral)

Performance of the 2-back task was analyzed using an ANOVA with percentage of correct responses in the 2-back task as dependent variable and group as between-factor revealing a significant main effect of group (see Table 11). Post-hoc pairwise Bonferroni-corrected comparisons showed that the participants in the negative group responded significantly more accurately than the participants in the positive group, p = .007, d = .79, and in the neutral group, p = .006, d = .79. There was no significant difference between the positive group and the neutral group, $p \geq .99$, d = .01. When reaction time was used as dependent variable and group as between-factor,

the main effect of group did not reach significance (see Table 11). Post-hoc pairwise Bonferroni-corrected comparisons revealed no significant differences between groups, p's ≥ .269, d's ≤ .38.

5.4.3 Testing the moderation hypothesis of executive functioning in the three groups with a parallel executive task (negative, positive, and neutral)

To analyze whether the performance in the GDT was moderated by executive functions when the 2-back task with negative, positive, or neutral stimuli was performed simultaneously, we calculated potential interactions using a moderated regression analysis with GDT net score as dependent variable and "MCST: Perseverative errors" (as a measure of executive functions) and "group" (neutral vs. positive, neutral vs. negative, negative vs. positive) as predictor variables (variables centralized, see J. Cohen, et al., 2003).

Table 13 Moderator analysis with group and MCST: Perseverative errors as predictor variables.

	β	*T*	*p*	Changes in *F*	*df1, df2*	Changes in *R*
DEPENDENT VARIABLE: GDT NET SCORE						
MODEL A: NEUTRAL vs. POSITIVE (*n* = 75)						
Main effects						
Group	-.32	-2.89	.005	8.37	1, 73	.10
MCST: Perseverative errors	-.43	-4.36	< .001	18.99	1,72	.19
Interaction						
MCST: Perseverative errors × group	-.27	-2.59	.012	6.70	1,71	.06
MODEL B: NEUTRAL vs. NEGATIVE (*n* = 74)						
Main effects						
Group	-.27	-2.38	.020	5.65	1, 72	.07
MCST: Perseverative errors	-.16	-1.40	.166	1.96	1,71	.03
Interaction						
MCST: Perseverative errors × group	-.25	-1.83	.072	3.34	1,70	.04
MODEL C: NEGATIVE vs. POSITIVE (*n* = 75)						
Main effects						
Group	-.12	-1.07	.290	1.14	1, 73	.02
MCST: Perseverative errors	-.53	-5.19	< .001	26.93	1,72	.27
Interaction						
MCST: Perseverative errors × group	.02	0.13	.899	.02	1,71	< .001

Table 13 contains the values of the three hierarchical regression analyses. In the first hierarchical regression model's (Model A: neutral vs. positive) first step the predictor "group" explained 10 % of the variance of the GDT net score. In the second step the predictor "MCST: Perseverative errors" led to a significant increase of 19 % variance explanation. Including the interaction between both variables ("MCST: Perseverative errors" multiplied by group) in the third step led to additional 6 % explanation of variance, indicating a moderation effect of the "MCST: Perseverative errors". The overall variance explanation of the GDT net score was significant as well, R^2 = .35, F (3, 71) = 12.82, p ≤ .001. The simple slope analysis of the interaction showed a negative slope for the simple regression line representing the predictor "group" that was significantly different from zero, t = 4.02, p < .001, when the number of "MCST: Perseverative errors" was one standard deviation above the mean. The slope was not significantly different from zero, t = .25, p = .803, when the

number of "MCST: Perseverative errors" was one standard deviation below the mean. This interaction indicates that participants with good performance in the MCST (as shown by a low number of perseverative errors) performed well on the GDT independently of whether or not the 2-back task included pictures of positive valence. By contrast, participants with low performance in the MCST (indicated by a high number of perseverative errors) showed decreased performance in the GDT when the stimuli were positive as compared to neutral. The interaction effect is shown in Figure 16.

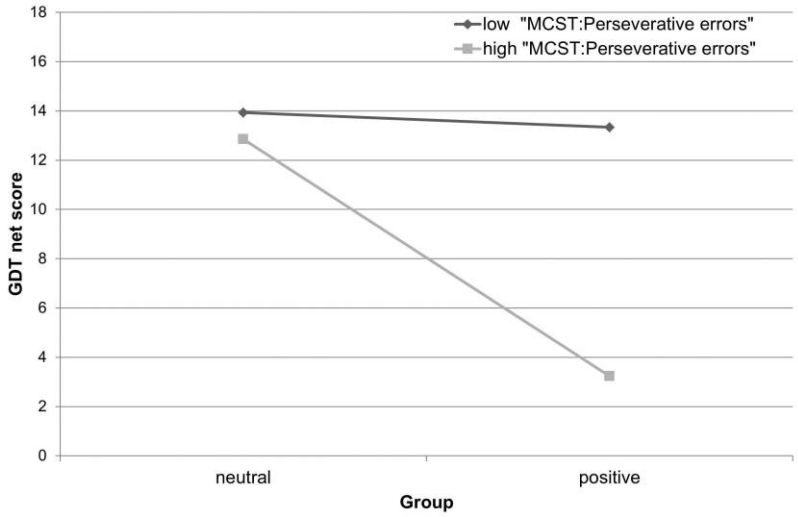

Figure 16 The interaction effect of the moderated regression analysis, with GDT net score as dependent variable and MCST: perseverative errors (as a measure of executive functions) and group (neutral vs. positive stimuli) as predictor variables.

In the second hierarchical regression model's (Model B: neutral vs. negative) first step the predictor "group" explained 7 % of the variance of the GDT net score. When entering the predictor "MCST: Perseverative errors" (second step), the explanation of variance did not increase significantly. By including the interaction between both variables ("MCST: perseverative errors" multiplied by "group") in the third step, further explanation of the GDT net score variance slightly failed to reach significance (see Table 13 for details). In sum, the overall variance explanation of the GDT net score was significant, $R^2 = .14$, F (3, 70) = 3.76, p = .015. However, the simple slope analysis of the interaction showed the same pattern as before: A negative slope for the simple regression line representing the predictor group that was significantly different from zero, t = 3.04, p = .003, when the number of "MCST: Perseverative errors" was one standard deviation above the mean. The slope was not significantly different from zero, t = .52, p = .607, when the number of "MCST: Perseverative errors" was one standard deviation below the mean. Even though the interaction effect slightly failed to reach significance, the pattern of the simple slopes indicates that participants with good performance in the MCST (low number of perseverative errors) performed well in the GDT independent of whether or not the 2-back task included pictures of negative valence. By contrast, when the stimuli were negative, participants with low performance in the MCST (high number of perseverative errors) showed decreased performance in the GDT. The interaction effect is shown in Figure 17.

In the first step of the third hierarchical regression model (Model C: negative vs. positive) the predictor "group" failed to reach significance (see Table 13 for details). But in the second step the predictor "MCST: Perseverative errors" explained 28 % variance of the GDT net score. When including the interaction between

both variables (MCST: Perseverative errors multiplied by group) in the third step, further explanation failed to reach significance. The overall explanation of the GDT net score was significant, $R^2 = .28$, $F\ (3, 71) = 9.37$, $p \leq .001$. Because the interaction explained less than 0.1 % of the overall variance, we did not analyze the simple slopes.

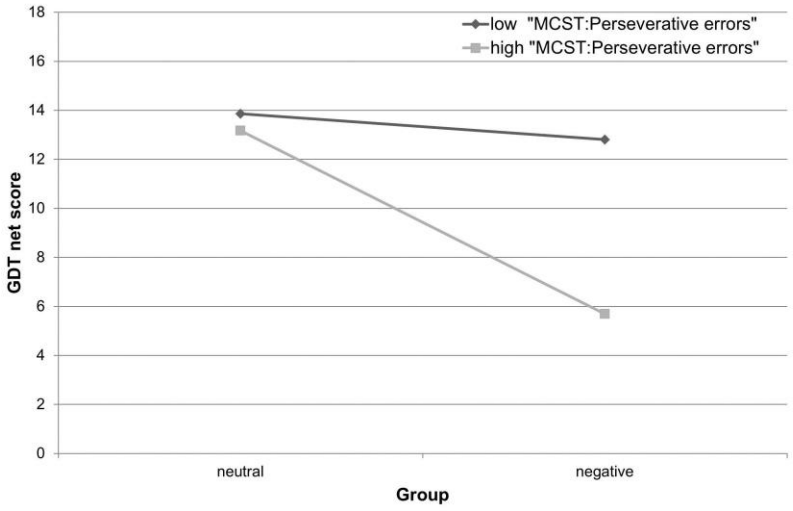

Figure 17 The interaction effect of the moderated regression analysis, with GDT net score as dependent variable and MCST: perseverative errors (as a measure of executive functions) and group (neutral vs. negative stimuli) as predictor variables.

5.5 Discussion

The results of the current study demonstrate that a parallel executive task involving affective pictures (of positive and negative valance) interferes with decision-making performance in a gambling task with explicit and stable rules compared to decision-making performance without a parallel task, even when controlled for working memory performance. In more detail, performing a parallel executive task with positive affective pictures simultaneously to the decision-making task leads to more disadvantageous decisions than performing a parallel task with neutral pictures. Even though the difference between negative and neutral pictures was not significant, there was at least a medium effect size (c.f. J. Cohen, 1992) indicating that negative pictures interfere with the decision-making performance as well. However, the comparison of the riskiest option between the negative and the neutral group did not show such an effect. In contrast, a parallel task with neutral pictures does not interfere with decision-making performance when compared to a group performing the GDT without additional task. Additional analyses regarding the use of feedback during the GDT revealed that participants performing a parallel executive task involving affective pictures used the feedback in the GDT less often than the GDT-solely group or the neutral group. A further main result of our study was that the influence of affective stimuli on decision making is moderated by the participants' executive functions. Participants with good executive functions are less influenced by the affective stimuli of the parallel task than subjects with lower executive functions.

These results support the findings by Starcke and colleagues (2011) stating that the performance of the GDT diminishes when a parallel tasks produces additional load on the executive system. The current results

demonstrate that processing affective pictures (in particular those with positive valence, see discussion below) in the 2-back task interferes more strongly with the decision-making task than processing neutral pictures in the 2-back task. Moreover, the results concerning the use of feedback in the GDT lead to the suggestion that processing affective pictures reduces the resources of the affective way (related to system 1; see section 3.4.1.1), which was shown to be involved in decision making under risk (Brand, Grabenhorst, et al., 2007; Brand, et al., 2006; see also section 3.1.2.2). Due to the fact that the cognitive resources (related to system 2; see section 3.4.1.1) are also reduced by the 2-back task itself, the additional load on the affective way leads to an even worse performance than a 2-back task with neutral pictures. Given that participants with superior executive functions are not affected by the affective stimuli, it seems that executive functions can compensate the negative impact of affective stimuli on GDT performance. Therefore, system 2 seems to be more crucial in decision making under risk than the intuitive-experiential system (system 1; Kahneman, 2003). This is in line with the findings by Starcke and colleagues (2011) as well as findings by Brand, Heinze, and colleagues (2008) and Brand, Laier, colleagues (2009), which also emphasize the importance of system 2 for decision making under risk.

5.5.1 Decision-making performance

Even though the results support the finding that GDT performance diminishes when a parallel executive task is performed simultaneously, they also demonstrate that this effect appears to depend on the stimuli included in the parallel 2-back task. When neutral pictures are included in the 2-back task, it does not seem to affect the performance of the GDT. Comparing findings on a descriptive level from studies using n-back tasks with different stimuli (digits vs. pictures) support this result: A recent study by Laier and colleagues (2012) found that performing a 4-back task with neutral pictures solely, led to an accuracy score of 80 %. In comparison, studies using a 2-back task (which is known to have a lower executive load than a 4-back task and thus should be easier to perform) with digits instead of pictures led to an accuracy score of only 66 % (mean accuracy rate: .66; Keeser et al., 2011) and 81 % (error rate of 17,8 %; Knops, Nuerk, Fimm, Vohn, & Willmes, 2006). These results imply that an n-back task with pictures is easier to perform than an n-back task with digits. This might be the reason for the good performance in the group with the neutral picture condition in our study.

Furthermore, our results are in line with previous studies that showed that subjects pay more attention to affective than to neutral stimuli (for a review see Vuilleumier, 2005). In his review, Vuilleumier (2005) referred to results of studies that made him to suggest that in situations where the attentional resources are limited, affective information is more salient and therefore receives preferential access to attention and awareness. Moreover, he proposed that these effects are involuntary and reflexive. With respect to our results one may argue that due to the fact that participants had to perform two tasks simultaneously, the attention resources were limited and that the affective stimuli had prioritized access. This might explain the reduced performance in the GDT when affective pictures are presented in the n-back task because attention is directed to the parallel executive task with affective stimuli. Pessoa (2009) also pointed out that affect-laden items that are task-irrelevant impair performance on the main task because affective information might be directly transferred to control structures and receive prioritized attention. Following the arguments by Pessoa (2009) and those by Vuilleumier (2005), may lead to the assumption that in the current study the affective pictures in the n-back task negatively influenced performance in the GDT because of binding attention resources.

When looking at our results in more detail, we found that particularly positive affect of the pictures had a negative influence on decision making under risk. Participants tended to decide more disadvantageously when performing a parallel executive task with positive stimuli simultaneously than to a parallel task with neutral or negative stimuli. This is in line with studies demonstrating that when the cognitive resources for analytic deliberation are reduced, subjects rely more often on heuristic, affective processes (Dijker & Koomen, 1996; Finucane, Alhakami, Slovic, & Johnson, 2000). Moreover, it was found that positive affect led to more risk-seeking behavior (e.g., Cheung & Mikels, 2011; Heilman, et al., 2010; Romer & Hennessy, 2007; Yuen & Lee, 2003), whereas negative affect entails risk-aversion (Alhakami & Slovic, 1994; Slovic, et al., 2004). Positive affect leads to an underestimation of the risk factor while the estimation of the benefit increases, resulting in risk-seeking behavior. On the other hand, negative affect leads to an increase in the perceived risk and to a decrease in the perceived benefit of a decision (c.f. Finucane, et al., 2000). Thus, assuming that the affective pictures in our study induced the equivalent affect in the participants, the positive group engaged in more risk-seeking behavior than the negative group resulting in inferior decision-making performance. Further support for our results comes from a study by Bagneux, Bollon, and Dantzer (2012) using a modified version of the GDT (with 30 trials instead of 18). Even though the difference slightly failed to reach significance, the data displayed, at least on a descriptive level, that in the last three blocks (out of five; six decisions were taken together to one block) participants who had watched happy video clips prior to performing the GDT more frequently chose the disadvantageous options than those participants who had watched angry video clips (the study is in detail described in section 3.4.2.2.2.).

Concerning the model of decision making under risk (Brand, et al., 2006; see also section 3.1.1) two different but interacting ways to decide advantageously are suggested: the cognitive way by using a decision strategy and the affective way by relying on one's intuition and experience. Assuming that the affective stimuli in our study led to an equivalent affect, it is possible that the positive affect reduces (executive) task performance such as executive capacity (Spies, et al., 1996) and planning performance (Oaksford, Morris, Grainger, & Williams, 1996). Since executive functions play an important role in decision making under risk, reductions in the executive domain lead to disadvantageous decisions (Brand, Grabenhorst, et al., 2007; Schiebener, et al., 2011; Starcke, et al., 2011). These findings support our data suggesting that particularly positive affective stimuli in the working memory task are linked to riskier performance in the GDT.

Regarding the affective way it may be possible that the GDT-irrelevant affect of the 2-back task (due to the affective stimuli) interfered with affective processing in the decision-making process. This was already shown for decisions under ambiguity (Laier, Pawlikowski, & Brand, 2013; Preston, et al., 2007; Van den Bos, et al., 2009): Task-irrelevant affect created interference with task-related affect (somatic markers; for more information about somatic markers and the involvement in decision making see chapter 3.1) necessary for advantageous decisions. Furthermore, first findings indicate that stress as a task-irrelevant affect impairs decision-making performance, also in decision making under risk (c.f. Starcke, et al., 2008). Therefore, the current results seem to be in line with the study by Starcke and colleagues (2008) and may support the assumption of the model of decision making under risk (Brand, et al., 2006; see also section 3) that task-irrelevant affect processing could interfere with feedback processing that lead to weakened decision-making performance.

Overall, the results demonstrate that positive affective stimuli lead to a higher frequency of the riskiest alternative than negative affective stimuli. However, regarding the overall performance of the GDT (GDT net score) this influence diminishes, leading to a reduced of GDT performance independent of affective valence. Additionally, both affective groups (negative and positive) seem to be impaired in feedback-processing.

5.5.2 Working memory performance

Working memory performance also appears to be influenced by affective stimuli. While Kensinger and Corkin (2003) as well as Perlstein and colleagues (2002) found better performance in an n-back task with pleasant stimuli, participants in our study showed superior performance in the 2-back task with negative stimuli in comparison with neutral and positive stimuli. In line with the current findings are studies that illustrated that positive affect leads to inferior performance in certain working memory processes like switching, encoding, and updating of information (E. A. Martin & Kerns, 2011; Phillips, Bull, Adams, & Fraser, 2002). Combined with the findings that positive affect reduces (executive) task performance such as executive capacity (Spies, et al., 1996) and planning performance (Oaksford, et al., 1996) this indicates that particularly the executive domain of working memory is disturbed by positive stimuli. Additionally, Levens and Gotlib (2010) demonstrated that healthy control participants need more time to disengage from positive stimuli in comparison with neutral and sad stimuli. Assuming that for the GDT with parallel 2-back task switching, updating of information, and disengaging from pictures are required, it seems plausible that the group with negative pictures (and therefore faster disengaging abilities) in the 2-back task appears to show better performance in both tasks than the positive group, at least when looking at the choice of the riskiest option. Moreover, Erk, Kleczar and Walter (2007) suggest that the right dlPFC is conducive to the integration of working memory and (mainly negative) affective processing. Activation in this brain area was generally stronger for high cognitive load than low cognitive load and additionally increased when the processed stimuli had an affective context. The authors interpreted this effect as an effort of an executive region to avoid impaired performance. The additional effort of the executive region (dlPFC) could be the cause for better performance of the negative group (compared to the positive group) in the 2-back task as well as in the GDT, given that activation of the dlPFC is also associated with GDT-performance (Labudda, et al., 2008).

5.5.3 Moderation effect of executive functions

A further important result of the current study is that the effect of affect-associated interference of decision making while performing a parallel task is moderated by the subjects' general executive functioning. When entering the positive and the neutral group in the model of the moderated regression the interaction between executive functions and group reached significance, indicating that the influence of affect (in this case the positive affect) on the decision-making performance is moderated by executive functioning (see section 5.4.3, Model A). When entering the negative and the neutral group in the model of the moderated regression the interaction did not reach significance (see section 5.4.3, Model B). Nonetheless, the simple slopes showed a comparable pattern to the slopes of the interaction in Model A. This finding supports earlier results that executive functions play an important role in decision making under risk (Brand, et al., 2006; Brand, Laier, et al., 2009) and it explains inter-individual variance in the GDT (Brand, Heinze, et al., 2008). Two essential processes of the executive functions are selective attention and task management (E. E. Smith & Jonides, 1999;

for detailed information see section 3.2). Therefore, participants with superior executive functions are more capable of concentrating on a goal and managing two tasks simultaneously even when one of the tasks deals with affective pictures, which usually receive more attention (see Vuilleumier, 2005 for a review). Furthermore, these results indicate that executive functions can possibly compensate the affective influence and support the assumption that aspects of system 2 are more important for decision making under risk (Brand, Laier, et al., 2009; Starcke, et al., 2011): Because even though the affective pictures seem to interfere with the GDT-performance and subsequently led to disadvantageous decisions (probably by using affective processing resources and therefore aspects of system 1 which are thus reduced for the GDT), those participants with good executive functions (and therefore aspects of system 2) seem to be unaffected and demonstrate advantageous decision making.

5.5.4 Limitations

There are some limitations to our study, which should be regarded. First, even though Starcke and colleagues (2011) demonstrated that a parallel executive task reduces the executive resources and therefore the GDT performance, we found no influence of the parallel executive task with neutral pictures. As already discussed, we believe that an n-back task with neutral pictures leads to less executive load than an n-back task with digits, because it is easier to perform. However, the comparison we mentioned is only descriptive. Future studies should investigate this in more detail by comparing the performance of two n-back tasks with different stimuli (digits vs. pictures). Second, we did not measure whether the pictures led to different affect and therefore, we can only speculate that the pictures induced different affective states, leading to different task performance between groups. However, the stimuli that were used in this study are derived from a well-validated extensively studied stimulus set (Lang, et al., 2008), which is often used to induce affective states (e.g., Dolcos, et al., 2008; Dolcos & McCarthy, 2006; Erk, et al., 2007; Kensinger & Corkin, 2003). Additionally, even though we did not investigate different states of affect, we could show that processing different affective stimuli diminishes the decision-making performance, at least when included in a parallel executive task, which is known to reduce executive resources for the decision-making task.

5.5.5 Conclusion

We conclude that processing task-irrelevant affective information interferes with decision making under risk and that this effect is moderated by executive functions. The results give first evidence for a mechanism that may explain why decisions in everyday life can become riskier for some individuals when affective stimuli divert attention and therefore interfere with the decision-making process. The impact of the interference seems to depend on the valence of the affect and on the individuals' executive functioning. The results support the assumption that the cognitive and the affective route interact in decision making under risk. However, it seems that executive functions and therefore aspects of system 2 are more crucial for decision making under risk: Executive functioning can compensate the negative influence of processing affective pictures. Future studies may investigate this issue in more detail, for instance by inducing different affective states experimentally and by using other affective parallel tasks. Furthermore, investigating brain correlates in this and comparable paradigms (e.g., with fMRI) could further contribute to the discussion about the interaction between affect, decision making, and executive functions.

6. Study 3: Monitoring, a key function of dual tasking: Decision making under risk and a parallel executive task

6.1 Abstract

It is assumed that decision making under risk (e.g., operationalized by the GDT) loads onto the analytical-rational system (system 2) that processes information serially. Consequently, the decision-making performance diminishes when performing an additional executive task simultaneously. Underlying mechanisms of the processes of system 2 are still unclear. Dual-tasking studies suggest that performing two tasks simultaneously requires executive functions, in particular a supervisory/monitoring function. The current study investigates the underlying executive functions of the GDT in a dual-tasking situation. Previously, simple relationships between GDT and executive functions were examined. To get a better understanding of the interplay of executive functions and dual tasking and the potential role of the supervisory/monitoring ability, a structural equation model (SEM) was calculated. Results support findings that executive functions are important in decision making and emphasize the assumption that the supervisory/monitoring function is crucial when performing an additional task simultaneously.

6.2 Introduction

Decision making is a key function in peoples' everyday life. In some situations people need to make decisions while performing an additional task simultaneously. It was found that in decision making under risk, in which the consequences of a decision and their probabilities are clear or at least computable, the decision-making performance diminishes when an additional executive task has to be performed simultaneously (Starcke, et al., 2011). In order to operationalize decisions under risk, Starcke and colleagues used the GDT (Brand, Fujiwara, et al., 2005; see also Table 1), which involves executive functions as well as affective processing (see section 3.1.2.2 and 3.2.2.2). However, it was shown that although processing of the affective feedback from previous decisions is of value to perform well in the GDT (Brand, 2008), this relationship appears to be moderated by the individuals' cognitive functioning (Brand, Laier, et al., 2009). This finding supports the assumption that, even though the affective and the cognitive route are involved in risky situations, a decision can principally be made by relying on the cognitive route alone (Brand, et al., 2006; for detailed information see section 3).

In the study by Starcke and colleagues (2011) participants had to perform a 2-back working memory task simultaneously to the GDT (find a detailed description of this study in section 3.4.1.4.2). The results demonstrated that performing the GDT with a secondary executive task simultaneously leads to more high-risk/disadvantageous decisions, compared to a group performing only the GDT. This result in combination with the previous findings of the important role of executive functions in the decision-making process (see section 3.2.2.2), suggests that decision making under risk requires especially the system 2, which processes tasks serially, slowly, controlled, effortful, etc. (Kahneman, 2003; see also section 3.4.1.1 for more information about dual-process systems). Compared to system 1, which acts automatic, fast, parallel, effortless, etc., the capacity of system 2 is limited. This leads to an interference of two tasks belonging to system 2 (Kahneman, 1973; Pashler, 1998; for a detailed discussion about task interference and dual tasking see section 3.4.1.1). The GDT and the 2-back task revert to the same cognitive resource (system 2): Equally to the GDT the 2-back task is

associated with executive functions such as inhibition, updating, coordination/ reorganization of information, and comparison of stimuli (e.g., Conway, et al., 2005; Owen, et al., 2005). Thus, Starcke and colleagues (2011) argue that the GDT performance is decreased when a 2-back working memory task has to be performed simultaneously. However, even though the results by Starcke and colleagues support this assumption they also discovered a variance in the performance of the GDT, indicating that some peoples' decision-making performance was not or at least was less affected by the additional task. This raises the question which cognitive ability is required to work well on both tasks (GDT and 2-back) simultaneously.

As already mentioned, system 2 works serially (Kahneman, 2003) that means, while concentrating on one task set the second task set seems to be inhibited (for a review on inhibition in task switching see Koch, et al., 2010). Thereby, subjects' attention is narrowed to the prioritized task and is consequently shielded from competing distractors (Easterbrook, 1959). However, in order to switch back to the second inhibited task if necessary, this control mechanism simultaneously enables monitoring for potential second-task associated action information (Miller & Cohen, 2001; Plessow, et al., 2011). The involvement of monitoring in in complex situations in which more than one task has to be done, was also postulated by D. E. Meyer and Kieras (1997a, 1997b; see also section 3.4.1.1) as well as by Norman and Shallice (Norman & Shallice, 1986; Shallice & Burgess, 1991a; 1991b; see also section 3.2). They assumed that a supervisory/monitoring function has to be involved in demanding situations in which an adaption to changing circumstances is necessary (e.g., in dual-tasking situations). An experimental study by D'Esposito (1995) supports this assumption by demonstrating the involvement of cortical areas associated with executive functions during dual tasking. However, as postulated by different authors (e.g., Miyake, et al., 2000; E. E. Smith & Jonides, 1999) executive functions can be divided into different subfunctions (for detailed information about executive subfunctions see section 3.2). The question remains which specific executive subfunctions may be involved in dual tasking. E. E. Smith and Jonides (1999) differentiate between five subfunctions (attention and inhibition, task-management, planning, monitoring, and coding) and demonstrated that task-management appears to be involved in dual tasking. Findings of further studies that investigated the underlying executive functions in dual tasking indicated that control functions (De Jong, 1995) as well as monitoring that means, updating and controlling the actual content of working memory in order to determine the next step and set-shifting (Cooper, et al., 2012), appear to be involved. These findings lead to the assumption that in order to make advantageous decisions under risk while performing an additional executive task simultaneously (as was suggested by the variance of the data by Starcke et al., 2011) enhanced monitoring abilities are required.

6.2.1 The current study

The current study was conducted to investigate this assumption. To clarify the relationship between the performance of a decision-making dual task, executive functions, and the special role of the supervisory/monitoring function we used a structural equation model (SEM). Analogously to the study by Starcke and colleagues (2011) we used the GDT plus 2-back task. Based on the fact that in both tasks (GDT and 2-back task) various executive functions such as comparison of information /categorization of information and feedback processing, are involved (e.g., Conway, et al., 2005; Euteneuer, et al., 2009), it can be assumed that those executive functions are involved in the GDT plus 2-back performance, too. However, to work on both tasks simultaneously and to do so equally well, as it is indicated by the GDT plus 2-back task, especially

monitoring abilities should be required: Both tasks and the current progress of each task need to be represented in working memory. Thereby, subjects should be able to perform one of the two tasks while the contemporary process of the second task should also be present simultaneously in order to switch back at an appropriate point in time. Taking these consideration into account, we assume that various executive functions such as categorization of information and feedback processing, as involved in the GDT and the 2-back task, influence the dual-task performance (GDT plus 2-back) directly (see the SEM-model in Figure 18). Moreover, we assume that those executive functions are also involved in the supervisory/monitoring process between the GDT and the 2-back task. Therefore, a mediation model is suggested (see Figure 18): On one hand executive functions should influence GDT performance directly. On the other hand this effect should be mediated by a supervisory/monitoring function because of its assumed key function in dual tasking. Subsequently, besides categorization and feedback processing, the supervisory/monitoring function should explain a noteworthy proportion of variance of the GDT plus 2-back task.

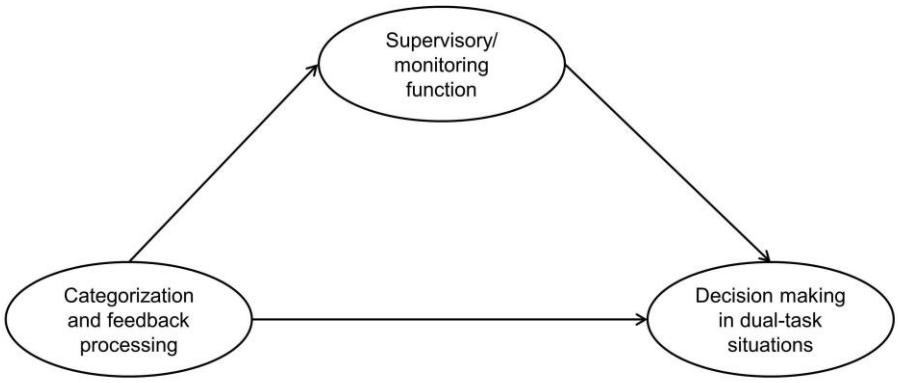

Figure 18 The theoretical mediation model.

It displays the possible mediation effect of the latent dimension *monitoring* on the relationship between the executive functions like categorization and feedback processing and decision making in a dual-task situation. The arrows represent the assumed direction of the influence of the different variables.

Based on the theoretical considerations above, we assume that participants with higher executive functions in general perform well in the GDT plus 2-back task. A substantial part of the executive functions should be explained by monitoring, which itself influences the GDT plus 2-back performance. However, because further executive functions should be involved in this dual task a partial mediation is suspected (c.f. Figure 18.

6.3 Methods

6.3.1 Participants

Overall we examined 122 right-handed participants (mean age: 31.06, *SD* = 13.07 years; 62 females). The participants were students of the University of Duisburg-Essen as well as their relatives and friends. The participation was voluntary and the participants received either credit points or a financial compensation at an hourly rate of € 10. As determined by a self-report questionnaire none of them had a history of neurological or psychiatric diseases. All participants demonstrated average, estimated IQ performance, measured by the subtest

four (reasoning) of the German intelligence test battery *Leistungsprüfsystem* (LPS; Horn, 1983), *M* = 117.03, *SD* = 11.95. Participants with an age higher than 50 were also screened for dementia with the DemTect (Kalbe et al., 2004). None of them had a score lower than 13, indicating no signs of mild cognitive impairment or dementia. All participants gave written informed consent. The study was approved by the local ethics committee.

6.3.2 Instruments

In reference to the theoretical model postulated in the introduction, the different variables were operationalized as followed: As a measure of decision making under risk in a dual-tasking situation the GDT plus a parallel executive task (2-back) was used (c.f. Schoofs, et al., 2008; Starcke, et al., 2011). In order to operationalize the executive functions, categorization and feedback processing the MCST (Nelson, 1976) was applied. We developed a new task to assess the supervisory/monitoring function that was based on the voluntary switching task by Arrington and Logan (2004) in order to measure not only task-switching functions but especially monitoring abilities. All tasks used are now described in detail.

6.3.2.1 Dual tasking: Game of Dice Task (GDT) plus a parallel executive task (2-back)

The same dual-task paradigm, which was used in the study by Starcke and colleagues (2011), was applied in the present study. It included a decision-making task with explicit and stable rules - the GDT (Brand, Fujiwara, et al., 2005) - and a parallel working memory 2-back task (c.f. Schoofs, et al., 2008). Both tasks were presented on the same computer screen: The 2-back task was embedded into the GDT interface, such that the 2-back task was presented on the left of the screen while the GDT was on the right side (see Figure 19). In order to work on both tasks simultaneously, participants had to use their left hand for the 2-back task and the right hand for the GDT. The participants were told perform to work on both tasks to the best of their abilities and to put equal effort into working on each task.

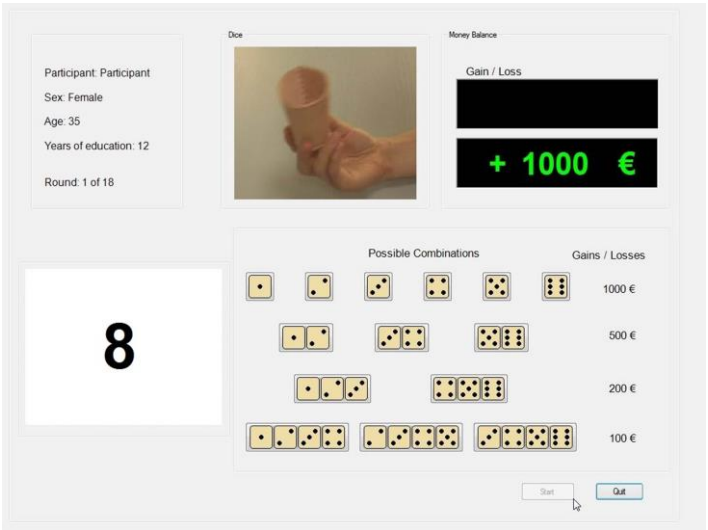

Figure 19 GDT plus 2-back task.

On the right side of the screen, participants work on the GDT by betting which number will be thrown next. On the left side of the GDT interface, participants must solve the 2-back task. Here, they need to continuously monitor the numbers presented and have to indicate whether the current number was presented two trials before or not, by keyboard input.

The GDT is a computerized task that is often used to operationalize decision making under risk (c.f. Gleichgerrcht, Ibanez, Roca, Torralva, & Manes, 2010). In this task participants aimed to maximize the fictitious starting capital of €1,000. During the 18 trials in which one virtual die was thrown, participants were asked to guess which number will be thrown next. In order to comply with the aim participants were asked to bet on one single number or on a combination of two, three, or four numbers by clicking the respective button using the computer mouse. They won if the chosen number or one number out of the chosen combinations of numbers were thrown, otherwise they lost. The options as well as the possible gains and losses were permanently shown on the screen. Each option offered was associated with different winning probabilities. When choosing one single number (e.g., six) the winning probability was 16.67 % to gain €1,000. If one of the other five numbers was thrown (one, two, three, four, or five) €1,000 were lost. Choosing the combination of two numbers (e.g., three and four), led to a gain of €500 with a probability of 33.33 %. However, if one of the other four numbers was thrown (one, two, five, or six) participants lost €500. The combination of three numbers (e.g., one, two, and three) provided a gain of €200 with a winning probability of 50 %. If one of the other three numbers was thrown (four, five, or six) they lost the same amount. With a winning probability of 66.67 % the choice of the combination of four numbers (e.g., three, four, five, and six) led to a gain of €100 and if one of the other two numbers was thrown (one or two) participants would lose €100. Following each decision participants received visual feedback about the amount of gain (colored green) or loss (colored red). Furthermore, the current capital and the remaining rounds were also permanently shown on the screen. In total, the options were categorized into advantageous/low-risk decisions (combinations of three and four numbers with a winning probability of 50 % and higher) and disadvantageous/high-risk decisions (one single number and combinations of two numbers with a winning probability of less than 34 %). Choosing the advantageous options all the time statistically led to a positive outcome in the long run, given the starting capital of €1,000. Therefore, the combination of three numbers was also classified as low risk in accordance with other studies before (e.g., Bayard, Abril, et al., 2011; Brand, Pawlikowski, et al., 2009).

The 2-back task had to be performed simultaneously to the GDT. In the small window on the left side of the GDT interface participants were shown numbers between 0 and 9 in succession. They were asked to monitor whether or not the currently presented number was identical with the number two trials before. The digits were displayed for 500 ms with an interstimulus interval of 2,750 ms. In the time frame of 500 ms participants were asked to indicate their answer by pressing one of two keyboard buttons (e.g., "c" for yes, digits were identical and "x" for no, digits were not identical). If no answer was given the trial was counted as a skip. The target stimuli, the same stimulus as two trials before, were displayed randomly with a probability of 33 % (adapted from Schoofs, et al., 2008).

In order to analyze the performance in the GDT, a net score was calculated by subtracting the number of high-risk decisions from the number of low-risk decisions. A positive net score indicated advantageous decision-making performance. Moreover, the percentage of low-risk/advantageous decisions was calculated. In order to analyze the performance of the 2-back task the percentage of correct reactions (i.e., correct identification and correct refusal as a target digit) were computed. For the analysis of the overall performance of the GDT plus 2-back task, the mean of low-risk/advantageous decisions in the GDT in percent and the percentage of the correct answers in the 2-back task were computed. The overall performance of the GDT plus 2-back task was used as a main measure of the dual-tasking performance and included in the SEM.

6.3.2.2 Modified Card Sorting Test (MCST): Categorization and feedback processing

The MCST was mostly used to measure subfunctions of executive functioning, involving set-shifting, categorization, cognitive flexibility and the ability to use feedback (see Lezak, et al., 2004; Strauss, et al., 2006). In this computerized test participants were asked to sort 48 cards (one at a time) onto one of four card decks presented on the screen according to a particular predetermined rule that was unknown to the participants. The symbols on the cards differed with respect to shape, color, and amount of symbols. Accordingly, the cards were sortable in three ways: by the shape, the color, and the number of the stimuli on the cards. To find out which sorting rule to follow, participants had to figure out which rule to apply by try-and-error using the provided feedback (right or wrong). The rule changed after six successively correct responses. As a main measure of categorization and feedback processing the number of perseverative errors (when the participant continues to sort the cards according to the previous rule though it had been indicated that the rule had changed) was used in the current SEM.

6.3.2.3 Balanced Switching Task (BST): Supervisory/monitoring function

Based on the voluntary task switching paradigm used by Arrington and Logan (2004) we developed a Balanced Switching Task (BST) to assess not only task-switching functions but especially monitoring abilities. In the task version of Arrington and Logan participants saw numbers on a screen between one and nine. They had either to indicate whether the current number on the screen is odd/even or whether the number is lower/higher than the number five. Participants were required to only do one task during a trial, which task they could decide voluntarily.

We modified the task in order to increase its load on monitoring. In this computerized task participants have to deal with four tasks, which they are asked to perform with equal effort. To comply with the aim participants had to voluntarily switch between tasks. The BST consisted of two sets of stimuli: Set A contained numbers from “01” to “99” and set B contained abstract geometric shapes that were diagonally hatched (see Figure 20 set B). In each set participants could principally work on two tasks respectively. Responses were made on a QWERTZ Keyboard using the keys “d” (left middle finger) and “f” (left index finger) as well as “j” (right index finger) and “k” (right middle finger). In set A, task 1 required to indicate whether the currently presented number was odd (“d”) or even (“f”), while in task 2, participants were asked to indicate whether the presented number was smaller (“j”) or greater (“k”) than the number 50. To avoid confusion, the number 50 itself was not part of the stimuli. In set B, task 1 required to indicate whether the hatching of the currently presented shape goes left (from the right lower corner of the shape to the left upper corner) by pressing “d” or right (from the left lower corner of the shape to the right upper corner) by pressing “f”. In task 2 of set B, participants were asked to indicate whether the presented shape is oriented vertically (“j”) or horizontally (“k”). At the beginning of the game participants could chose with which task set they would prefer to start. Within each task set (A and B) only one stimulus at a time was presented and participants could voluntarily choose which task (task 1 or 2) they would prefer to perform by pressing the associated keys (“d” and “f” for task 1 and “j” and “k” for task 2). To switch between task 1 and 2 within a set, participants just needed to use the respective pair of keys associated with the other task. To switch between set A and set B participants were told to press the spacebar. Thus, participants had to process only one out of the four tasks with each presented stimulus.

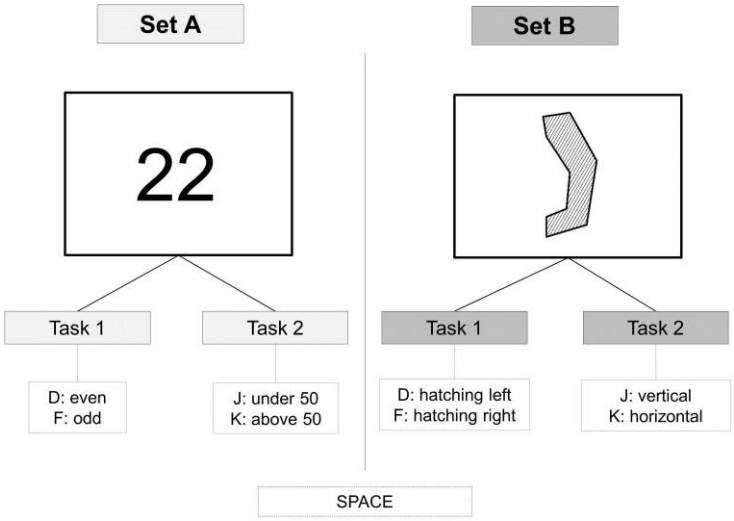

Figure 20 Schematic representation of the Balanced Switching Task.

The left side of the figure displays an example stimulus of set A and indicates which buttons participants have to use in order to perform task 1 (even or odd) and task 2 (smaller or greater than 50) of set A. The right side shows an example stimulus of set B and indicates which buttons participants have to use in order to perform task 1 (hatching left or right) and task 2 (figure vertical or horizontal) of set B. To switch between the two sets participants have to use the spacebar indicated by "space" in the figure.

Before the task started participants complete a practice block in which they learned how to work on the tasks. In this practice block, participants started to perform task 1 of set A only. This was followed by a short practice sequence of tasks 1 and 2 of set A in which participants could voluntarily switch between both tasks. Afterward, the participants practiced task 1 of set B only, followed by a practice sequence in which they could switch between task 1 and 2 of set B. At the end of the practice block participants had a short sequence in which they were asked to practice to switch between all tasks (i.e., including switching the sets via the spacebar). Furthermore, participants were informed about the three aims of the paradigm: to perform all four tasks in a balanced fashion, to classify the stimuli to the best of their ability, and to execute as many stimuli as possible in an unknown timeframe. Moreover, participants were informed that the switch between the two sets required a certain but unknown timeframe meanwhile they could not perform any of the four tasks and which was subtracted from the overall time. While this indicated that participants would have less time to process stimuli if they switched between sets too often, they did have to switch to work on all four tasks equally. The subjects were not informed about the overall duration of the paradigm nor the stimulus presentation times. Therefore, participants were not able to estimate how much time they would have to work on each task to achieve the best balance between all tasks. Information not given to the participants: In total, the task consisted of two blocks of 4 min each. A stimulus was presented until the participant responded but maximally for 1,000 ms. The interstimulus interval was 500 ms, a switch between set A and set B lasted 1,250 ms. After the first and second block, participants received feedback about the equability of the tasks performances in percent, the total accuracy in percent, and the number of correct responded stimuli.

In order to evaluate the supervisory/monitoring performance postulated in the SEM, the so called *deviation score* was computed for each block separately. The deviation score provides information about the deviation from the optimal equal performance calculated for each participant. The deviation score was calculated as followed:

$$\sqrt{\frac{(\text{task 1 Set A} - 25)^2+(\text{task 2 Set A} - 25)^2+(\text{task 1 Set B} -25)^2+(\text{task 2 Set B}-25)^2}{4}}$$

For each task the amount of presented stimuli in percent were calculated (e.g., presented stimuli of task 1 in set A divided by presented stimuli of block 1). In the formula above, this is displayed by task 1 set A, task 2 set A, task 1set B, and task 2 set B. From each of these results the optimal value of equal performance (25 %) was subtracted, and the outcome was squared. We calculated the mean from this equation and then calculated the square root of the mean. A deviation score of 0 testified of equal adaptation of all four tasks (i.e., perfect performance). A deviation of 43 indicates that the participant had only performed one task out of four (i.e., worst performance).

6.3.3 Statistical Analyses

For the statistical standard analyses IBM SPSS Statistics software for Windows (Release 19.0; April 18, 2011; SPSS Inc. IBM, Chicago) was used. To test for zero-order relationships between two variables Pearson correlations were calculated. In order to test the hypothesized mediation model, SEM analysis was done using Mplus 6 (Muthén & Muthén, 2011). For this the maximum likelihood parameter estimation was applied. There were no missing data.

The evaluation of the model fits were done by applying standard criteria (Hu & Bentler, 1995; Hu & Bentler, 1998; Hu & Bentler, 1999). The following fit indices were used: χ^2 test (non-significant values indicate that the data fit with the model), χ^2 /*df* (values between .00 and 2.00 indicate a good fit), root mean square of approximation (RMSEA; "test of close fit"; a value between .00 and .05 with a significance value between .10 and 1.00 indicates a good fit), standardized root mean square residual (SRMR; values between .00 and .05 indicate a good fit), comparative fit index (CFI; a value between .97 and 1.00 indicates a good fit), Tucker-Lewis Index (TLI; values between .97 and 1.00 indicate a good fit). Due to the fact that the TLI is not normed, the values can sometimes be outside the range of .00 to 1.00 (Schermelleh-Engel, Moosbrugger, & Müller, 2003). According to Baron and Kenny (1986) it is required that all variables included in the mediation correlate with each other.

6.4 Results

6.4.1 Descriptive data of task performance

Table 14 shows the mean performances of the participants in the different tasks. Compared with studies that used the original version of the GDT in healthy subjects demonstrating a net score around 10 (c.f. Brand, 2008; Brand, Heinze, et al., 2008; Brand, Laier, et al., 2009), the net score of the GDT version used here, was lower on a descriptive level. However, it was similar to the net score found in the study by Starcke and colleagues (2011) that previously used the GDT plus 2-back task. The correct responses in percent of the 2-back task performed simultaneously to the GDT were lower on a descriptive level than in studies in which participants had to perform only the 2-back task (Keeser, et al., 2011; Knops, et al., 2006). The performance in the MCST as well as the IQ were in a normal range (Horn, 1983; Lineweaver, Bondi, Thomas, & Salmon, 1999). The values of the newly developed BST were in line with the experience and findings we made in our laboratory so far (unpublished results). They indicate that the instructions of the tasks were understood and implemented. Moreover, the difficulty of the task seemed to be adequate: The mean of the deviation was about 10 %

indicating that on average the participants performed well on the tasks. Yet, there was variance in the performance (see range and standard deviation in Table 14) that suggests that some participants had difficulties in equal performance of the four tasks while others did not.

Table 14 Descriptive values of task performances of the sample.

Tests	Range	*M*	*SD*
GDT			
net score[a]	-18 - 18	7.03	9.57
low-risk decisions[b]	0 - 100	69.54	26.57
2-back task			
correct responses[b]	9.43 - 89.04	57.88	18.34
MCST			
perseverative errors[c]	0 - 8	1.13	1.78
BST			
deviation score block 1[d]	.00 - .43	.10	.10
deviation score block 2[d]	.00 - .43	.09	.09

[a]Low-risk decisions minus high-risk decisions. [b]In percentage. [c]Raw score. [d]Relative frequencies.

6.4.2 Correlations between dual task and executive functions

Nearly all measures of executive functions correlated significantly with the GDT plus 2-back task and have a small to medium effect size (c.f. J. Cohen, 1992; see Table 15 for the results). Only the variable *deviation score of block 2 of the BST* did not correlate significantly with the GDT plus 2-back task ($p = .066$).

6.4.3 The latent dimension

The high β coefficients of the two manifest variables of the BST (deviation score block 1: $\beta = .972$, $SE = .10$, $p \leq .001$; deviation score block 2: $\beta = .806$, $SE = .09$, $p \leq .001$) revealed that the latent dimension *supervisory/monitoring function* seems to be adequately modeled. Moreover, this is supported by the significant correlation, $p \leq .010$, of the two variables with a high effect size (see Table 15).

Table 15 Correlations between GDT plus 2-back task and executive functions.

		1	2	3	4
1	GDT plus 2-back[a]	-	-	-	-
2	MCST[b]	-.251**	-	-	-
3	BST (block 1)[c]	-.239**	.254**	-	-
4	BST (block 2)[c]	-.167†	.237**	.784**	-

[a]Mean of correct responses in the 2-back and low-risk decisions in the GDT (in percentage). [b]Frequency of perseverative errors (raw score). [c]Deviation score (deviation from the optimal value of equal performance). **$p \leq .010$. †$p = .066$.

6.4.4 Full structural equation model (SEM)

Testing the proposed model with GDT plus 2-back task (i.e., the mean of low-risk/advantageous decisions in the GDT in percent and the percentage of the correct answers in the 2-back task) as endogenous variable revealed a good fit with the data. The χ^2 test was not significant, indicating that the data do not differ significantly from the

model, $\chi^2 = 0.71$, $df = 1$, $p = .400$. The ratio of χ^2/df was below 2.00, the RMSEA had a value of 0.00 with $p = .468$, the SRMR was .01, the CFI was 1.00 and the TLI = 1.01.

6.4.4.1 The pathways of the full model

Figure 21 demonstrates that in total 10 % of the variance of the GDT plus 2-back task could be explained significantly by the model, $SE = .05$, $p = .031$. Monitoring, measured by the BST (i.e., deviation score of block 1 and block 2), as well as general executive functions, measured by the MCST (i.e., perseverative errors), explained the GDT plus 2-back variance significantly, SE's $\leq .09$, p's $\leq .018$. The β coefficients were negative because good performances in the MCST and BST were indicated by low values (depending on the variables used of these tasks: *Perseverative errors in the MCST* and *deviation score of the BST*).

6.4.5 Mediation analysis

In order to analyze whether or not monitoring is a key function of the executive functions explaining the variance of the dual-task performance (GDT plus 2-back task), a mediation analysis was computed. The indirect effect from MCST via the latent dimension *supervisory/monitoring function* on the GDT plus 2-back task was significant, $\beta = -0.05$, $SE = .03$ $p = .048$. The direct effect was significant as well, $\beta = -0.20$, $SE = .09$, $p = .012$, indicating a partial mediation effect of the latent dimension *supervisory/monitoring function* on the GDT plus 2-back performance (see Figure 21).

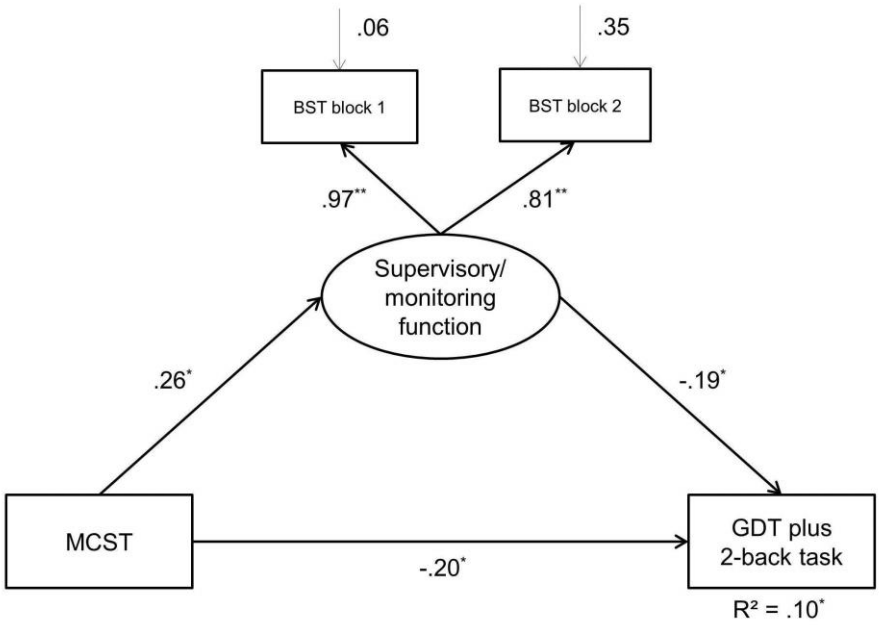

Figure 21 The full structural equation model.

The oval shape indicates the latent dimension while the rectangular shapes indicate the manifest variables. Bold arrows indicate direct effects while the non-bold arrows display errors. ** $p \leq .001$. * < .050. BST = Balanced Switching Task, measures the monitoring/supervisory function. MCST = Modified Card Sorting Test, measures categorization and feedback processing. GDT = Game of Dice Task, measure for decision making under risk. 2-back task = working memory task.

6.5 Discussion

The focus of this study was to explain the underlying functions of dual-task performance that means, when performing a parallel executive task simultaneously to a decision-making task. Based on the theoretical approaches of D. E. Meyer and Kieras (1997a, 1997b; see also section 3.4.1.1) and Norman and Shallice (Norman & Shallice, 1986; Shallice & Burgess, 1991a; 1991b; see also section 3.2.1) we assumed that the supervisory/monitoring function of the executive system plays an important role in dual tasking and partially mediates the relationship between various executive functions (e.g., categorization of information/stimuli and feedback processing) and the GDT plus 2-back task. The results of the current study support our theoretical model: The supervisory/monitoring function partially mediated the relationship between categorization of stimuli and feedback processing and the performance in the GDT plus 2-back task. That means that participants with good monitoring abilities decided more advantageously in the GDT while simultaneously demonstrating good performance in the 2-back task. Indeed, monitoring seemed to lead to a better dual-tasking performance also in a decision-making situation. However, the results indicate that independently of the monitoring function, executive functions such as categorization of stimuli and feedback processing, increase the performance in both tasks when performed simultaneously.

The current findings support several studies that argue that executive functions are important for dual tasking and that a supervisory/monitoring function plays a key role in that process (e.g., Cooper, et al., 2012; De Jong, 1995; D. E. Meyer & Kieras, 1997a; for detailed information see section 3.4.1.2; 1997b). Moreover, the study at hand possibly explains the variance in the GDT plus 2-back task found in the study by Starcke and colleagues (2011). In their study performing an additional executive task simultaneously to the GDT led to disadvantageous decision making compared with performance in the GDT on its own. However, some participants demonstrated no diminished GDT performance. The SEM of the current study suggests that superior monitoring functions may account for parts of that variance.

The fact that various executive functions influence the performance in the GDT plus 2-back task, independently of this monitoring function, may be explained by the circumstance that each component task is associated with executive functions beyond monitoring (Brand, Fujiwara, et al., 2005; Brand, et al., 2004; Brand, Recknor, et al., 2007; Conway, et al., 2005; Euteneuer, et al., 2009; Owen, et al., 2005). Furthermore, it seems plausible that in order to perform two tasks simultaneously more executive functions than monitoring are needed. For example, if we assume that a bottleneck appears at a certain point in a dual-tasking process, where only one task can be performed at a time (c.f. D. E. Meyer & Kieras, 1997a, 1997b), task switching, set-shifting, and inhibition should be further important executive functions (c.f. Cooper, et al., 2012; Koch, et al., 2010). Furthermore, the current findings support the assumptions of the involvement of monitoring in task shielding, which is involved in serial processing (Miller & Cohen, 2001; Plessow, et al., 2011) and therefore in system 2 (Kahneman, 2003): Superior monitoring functions enable the detection of second-task associated action information although the second task is inhibited while simultaneously performing the primary task.

The important role of executive functions for decision making under risk as postulated in a decision-making model (Brand, et al., 2006; see also section 3) becomes not only apparent in studies investigating the simple relationship between them (Brand, Recknor, et al., 2007; Brand, Roth-Bauer, et al., 2008; Euteneuer, et al., 2009); Their importance becomes more obvious in studies investigating decision making under risk in

demanding situations, such as a dual-tasking situations. In a recent study, participants did not only have to perform the GDT plus 2-back task, but were also stressed before the performance (Pabst, Schoofs, et al., 2013). Results demonstrated that stressed participants with superior executive functions showed better decision-making performance while simultaneously performing a 2-back task than stressed participants with low executive functions.

Those and the current findings emphasize the important role of executive functions in decision making in a dual-task situation. In particular, besides the direct influence of various executive functions, the present study demonstrates the involvement of the supervisory/monitoring function of the executive system. This is crucial for advantageous decision making in situations where people have to perform other tasks simultaneously. Moreover, the results give further insight into the organization of executive functions: Monitoring seems to be a function involved in the coordination of different actions and subfunctions. Thus, the findings are in line with the idea that monitoring seems to be a higher-level function, which manages different lower-level functions in order to achieve good performance (Miyake, et al., 2000; E. E. Smith & Jonides, 1999). However, at this point it has to be mentioned that the assumption that the assumption that the BST measures monitoring/supervisory functions is only theoretically: In this task participants have to remember how much time they had already spend on each task and to kept in mind that they would have to switch to the other three tasks to obey with the aim of balanced performance. According to Shallice, Stuss, Picton, Alexander, and Gillingham (2008) such ability is associated with monitoring. In the SEM the deviation score was used to operationalize monitoring (see section 6.3.2.3): The deviation score computes how often a person performed each of the four tasks in dependency from the overall trials and how much this deviates from a perfect balanced fashion (25 % each task). Even though it is from a theoretical perspective assumable that the deviation score depict the ability to monitor, it is not directly tested. Future studies should investigate whether this score correlates with other tasks known to operationalize the supervisory/monitoring function. Likewise, future studies should investigate the role of executive functions in decision making in dual-tasking situations in more detail. It may be of interest to know which specific executive functions are involved in this process: The demand of performing two tasks in parallel increases more and more in everyday life. Making important decisions while working on another task becomes daily routine, in professional as well as social life. So far, there are some studies demonstrating that after a training session laboratory dual-task performance increases (e.g., Bherer et al., 2005; Liepelt, Strobach, Frensch, & Schubert, 2011). Knowing which specific (executive) functions underlie the performance of decision making in parallel with additional tasks could help to develop dual-task trainings with more practical application in everyday life.

7. General discussion

In the last three chapters each study was discussed individually in detail (see section 4.5, 5.5, and 6.5). The following chapter will first summarize (section 7.1) and then discuss the findings more generally and join them in view of the current literature with a focus on decision making under risk (section 7.2). Moreover, a general conclusion and a perspective for future studies will be given (section 7.3).

7.1 Summary of the main results

All three studies were conducted in order to gather knowledge about the interaction between affective and cognitive processes in decision making under risk, but each study had a slightly different focus. The first study (see chapter 4) investigated the neural correlates of the interaction between decision making under risk, additional executive load, and stress. The fMRI study revealed that, on a behavioral level, the double burden of stress and additional executive load did not appear to impair the decision-making performance in a risky situation. However, imaging data revealed that this might be due to an increased activation in the aPFC, a brain region that is associated with parallel processing (Koechlin & Hyafil, 2007). The simultaneous negative correlation between activation in a brain area associated with serial processing and cortisol increase during this dual task supported this assumption. These findings seem to be in line with the assumption by Plessow, Schade, and colleagues (2012) and Pabst, Schoofs, and colleagues (2013) that stress might trigger the shift from serial to parallel processing by reduced task shielding and thus might facilitate decision making while performing an additional executive task in stressful situations.

The second study (see chapter 5) examined the effect of additional cognitive and varying affective load during decision making under risk. Therefore, participants had to perform an additional executive task involving affective pictures of varying valence and neutral pictures while making decisions. The results demonstrated that the processing of affective pictures (especially pictures of positive valence) interfered with the decision-making performance when compared with the simultaneous processing of neutral pictures or non-parallel processing, respectively. Moreover, the analyses revealed that, irrespective of the affective stimuli, executive functions moderate the relationship: Participants with superior executive functions appeared not to be impaired in their decision-making performance when performing an additional executive task involving affective pictures, while participants with inferior executive functions demonstrated disadvantageous decision making. These findings indicate that affective and cognitive processes interact in predicting decision making under risk.

The third study focused on the question which executive functions may be involved in decision making in a dual-task situation that means, when an additional executive task needs to be performed simultaneously (operationalized by the GDT plus 2-back task). The assumption that executive functions, such as categorization of stimuli and feedback processing, directly influence this dual-task performance and are probably partially mediated by the executive function monitoring, was supported by a SEM. This finding gives insight into the organization of executive functions and their involvement in decisions under risk: The supervisory/monitoring function appears to be involved in the coordination and management of different actions and subfunctions (e.g., categorization of the options presented and processing of the received feedback) in the decision-making process. Thus, the findings are in line with the idea of higher-level and lower-level executive functions, whereby the

higher-level functions, manage different lower-level functions in order to achieve superior performance (Miyake & Friedman, 2012; Miyake, et al., 2000; E. E. Smith & Jonides, 1999).

In the next section these findings will be discussed in the light of the current literature with regard to the core topics of the present thesis: decision making under risk and the potential role of stress, affect, executive functions and dual tasking. At last a general conclusion and perspectives for future studies will be given (see section 7.3).

7.2 Discussion of the presented findings

The overall aim of this thesis was to extend the knowledge about the postulated affective and cognitive processes in decision making under risk (Brand, et al., 2006; see following sections for detailed information 3, 3.1, and 3.2), in particular about their interaction. Therefore, situational effects, additionally loading onto the cognitive (e.g., an additional executive task) and affective route (e.g., stress or affective stimuli), were used. It was found that affective and cognitive processes interact in a way that they provide advantageous decision making in such demanding situations (Pabst, Schoofs, et al., 2013). In the present thesis it was of peculiar interest to examine the underlying neural correlates of this interaction and the cognitive mechanisms, possibly managing the decision-making process in this kind of situations. Figure 22 summarizes the findings of the three studies and of these the derived assumptions. Below the model will be outlined in detail.

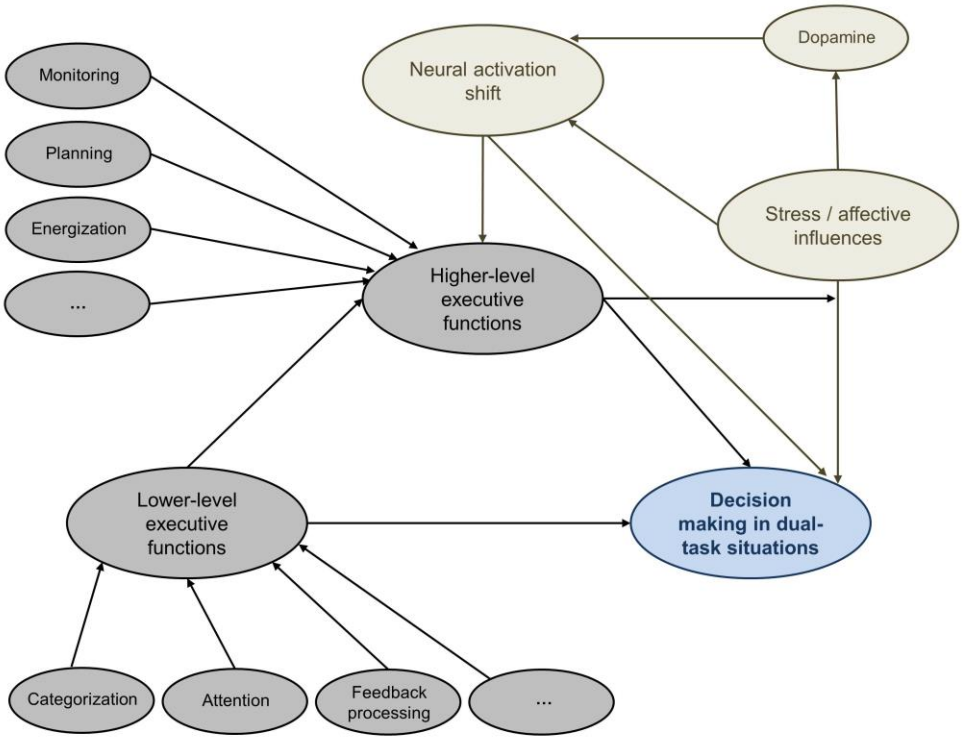

Figure 22 The interaction between cognitive and affective processes in decision making under risk with additional executive load.

The model summarizes the discussed findings and assumptions inferred from the three studies of this thesis. It displays the suggested hierarchy of the executive functions (colored in grey) and their influence on decision making under risk in dual-tasking situations (colored in blue). Moreover, the influence of affective influences such as stress and the associated neural mechanisms (colored in beige) are shown as well as their assumed interplay with cognitive processes.

A previous study demonstrated that decision-making performance under risk was reduced when an additional executive task was performed simultaneously (Starcke, et al., 2011). According to Kahneman (2003), two tasks belonging to system 2, which need to be performed simultaneously, are processed serially rather than parallel and interfere with each other (see section 3.4.1.1 for further information about dual-process theories). Therefore, Starcke and colleagues (2011) suggested that processes belonging to system 2 are particularly involved in decision making under risk (for detailed information about this study see section 3.4.1.4.2). However, when making a decision while have to perform an additional executive task in a stressful situation simultaneously, decision-making performance was not reduced (Pabst, Schoofs, et al., 2013; for a detailed discussion about this finding see section 3.4.4). This was in contrast to findings investigating the influence of stress on decision making under risk, demonstrating impaired performance on the same decision-making task but without additional cognitive demand (Starcke, et al., 2008). Pabst, Schoofs, and colleagues (2013) assumed that in demanding situations stress triggers a serial-to-parallel processing shift, which in turn enables superior task performance in both tasks (for a comprehensive discussion see section 3.4.4).

While the behavioral findings of the first study of the present thesis at (see section 4.4.2) also demonstrated no differences in task performance in such demanding situations, the neuroimaging findings did. They revealed that neural activity in parallel processing areas (aPFC; Koechlin & Hyafil, 2007) was increased during stress in this kind of situations, while serial processing areas (dlPFC; Dux, et al., 2006) were associated with a decrease of neural activity in stressful and cognitive demanding situations. Studies investigating the influence of stress on cognitive task performance while simultaneously examining neural activation demonstrated that stress leads either to a deactivation in task-associated brain regions, which is associated with decreased task performance (Oei, et al., 2007; Qin, et al., 2009), or to an increased activation in task-associated brain regions associated with superior task performance (Henckens, Van Wingen, Joëls, & Fernández, 2011). The findings of the first study of this thesis suggest that it might be the interplay of increased and decreased activations of certain brain regions that lead to comparable behavioral performance in stress as well as non-stressed participants. In particular, in complex and demanding situations, which involve stress as well as an additional cognitive demand that influences decision-making performance, an interplay between brain regions associated with serial and parallel processing occurs. This interplay is accompanied by a neural activation shift of these brain regions, which appears to be advantageously for superior decision-making performance (see the beige ovals in Figure 22; for a detailed discussion about this shift see section 4.5).

In terms of dual-process theories, this interplay is in line with the assumption made by Epstein (1994) that all behavior is assumed to be the product of the joint operation of system 1 and system 2. He postulated that the relative dominance of a system depends, among other aspects, of situational variables (for more details see section 3.4.1.1). The dual-task situation in study one (two effortful tasks) of the current thesis would thus assume that system 2 related processes appear to be dominant (Epstein, et al., 1996; Kahneman, 2003). In contrast, the stressful influence would rather suggest activation of system 1 related processes, due to the fact that affective arousal is considered to shift the dominance more in the direction of system 1 (Epstein, 1994), which is known to be associated with affect-based processes (Epstein, et al., 1996; Kahneman, 2003). Therefore, it is assumable that both processes interact in such demanding situations, which might be associated with the assumed shift from serial to rather parallel processing (i.e., from system 2 related processing to rather system 1 related processing).

However, the increased activation in the aPFC (in the first study of this thesis) leads to the suggestion that system 2 rather than system 1 processes appear to be more dominant because system 1 processes are more closely associated with brain regions associated with the limbic system (Evans & Stanovich, 2013; Goel & Dolan, 2003; McClure, Laibson, Loewenstein, & Cohen, 2004). In contrast, the aPFC builds together with other prefrontal regions the apex of the executive system (Koechlin, et al., 1999; Koechlin & Hyafil, 2007). Executive functions were found to be involved in system 2 related processes, such as managing two concurrent tasks (Cooper, et al., 2012; De Jong, 1995; see section 3.4.1 for a detailed discussion). Though, due to the additional involvement of this area in parallel processing this region might be a platform for the interaction between system 1 and system 2 related processes. Moreover, it was often shown that processing of affective influences (system 1 related) in situations in which cognitive functions (in particular system 2 related) are also necessary, leads to increased activation in cognitive-related regions supporting the assumption of the interaction between both processing types (see section 3.1.1 for a detailed discussion). Taken together, it appears that stress processed by system 1 related processes triggers a shift from serial to parallel processing, which is accompanied by increased activation of an area associated with parallel processing but also executive functioning (system 2 related). Executive functions are involved in dual tasking (see section 3.4.1.2) and decision making under risk (see section 3.2.2.2), and subsequently may facilitate the performance in the demanding decision-making situation (see connections between beige ovals and grey ovals in Figure 22).

The involvement of executive processes in a decision situation with additional cognitive demand was shown in the third study of the current thesis (see section 6). The results suggest that in particular a supervisory/ monitoring function (higher-level executive function) mediates (at least partially) the performance of lower-level executive processes (e.g., categorization of alternatives, and feedback processing) leading to increased decision-making performance in a situation with additional demand. This would be in line with several authors postulating that executive functions are distinguishable into lower-level and higher-level functions, whereby it is assumed that the higher-level functions manage the lower-level functions (Miyake, et al., 2000; Shallice, Burgess, & Robertson, 1996; Shallice, et al., 2008; E. E. Smith & Jonides, 1999; Stuss, Shallice, Alexander, & Picton, 1995). Lower-level functions are for example, shifting and updating (Miyake, et al., 2000), attention (E. E. Smith & Jonides, 1999), and contention scheduling (Shallice, et al., 1996; Stuss, et al., 1995). Higher-level functions include functions such as planning (Miyake, et al., 2000), task management (E. E. Smith & Jonides, 1999), and dimensions of the supervisory control framework (e.g., energization of schemas, adjusting contention scheduling, and monitoring the level of activity in the schemas; Shallice, et al., 2008; Stuss, et al., 1995). However, due to the partial mediation it is assumable that monitoring is not the only higher-level executive function involved in processing decision making in a dual-task situation. According to Shallice et al. (1996) and Stuss et al. (1995) a certain schema is activated to perform a task (including lower-level executive mechanisms). When two tasks need to be performed simultaneously, two schemas are activated and the supervisory control system is required to organize them. For example, it needs to energize the schema for one task and inhibit the schema of the second task while simultaneously monitoring the activation of the two schemas (Shallice, et al., 1996; Stuss, et al., 1995). These higher-level functions may also be involved in the performance of the decision-making task with simultaneous executive task (see grey colored ovals in Figure 22).

In sum, the findings of the first and third study lead to the suggestion that in stressful situations with additional cognitive demand, advantageous decision making might still be possible, because stress activates a

brain area associated with parallel processing and higher-level executive functioning, facilitating the performance of two concurrent tasks (see the connection between beige and grey colored ovals in Figure 22). This kind of facilitation effect of executive functions was also demonstrated in the second study of this thesis. In this study, it seems that superior executive functions compensated the negative influence of affective pictures. By including this finding into the overall model (Figure 22) it can be assumed that a neural activation shift leads to an increased activation of brain areas associated with executive functions, which again moderate the affective influence (see the connection between beige and grey colored ovals in Figure 22).

Finally, the combination of the three study findings of the current thesis, suggest a compensation effect. This might take place in decision-making situations with a double burden (additional affective influence and cognitive demand): Stress leads to an increased activation of a brain area associated with cognitive functions, facilitating the task performance in this kind of situation. Simultaneously, increasing stress level is associated with decreasing activation of a brain region, which in this kind of situation appears to be less supporting for task performance (Pabst, Schoofs, et al., 2013; Plessow, et al., 2012; for a detailed discussion see section 4.5). This assumption is based on studies demonstrating compensation effects in elderly people when performing cognitive tasks in comparison to younger adults (e.g., Bangen et al., 2012; Cabeza, 2002; Cabeza, Anderson, Locantore, & McIntosh, 2002; S. W. Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Grady, 2008). In these studies it was found that in cases where older people show similar cognitive performance to younger people, they also demonstrated increased activation in brain areas associated with cognitive task performance or activation in areas which might compensate the regions decomposed due to aging. An increased activation of prefrontal regions was most commonly associated with such compensational mechanisms (Cabeza, 2002; S. W. Davis, et al., 2008; Grady et al., 1994). This was found across different cognitive functions when tested in elderly for example, in working memory (Grossman et al., 2002; Rypma & D'Esposito, 2000) and attention (Cabeza et al., 2004; Madden et al., 2002). Recently, such compensation mechanisms were also found in adults with attention-deficit/hyperactivity disorder (ADHD; Dillo et al., 2010), alcohol dependent individuals (Chanraud, Pitel, Müller-Oehring, Pfefferbaum, & Sullivan, 2013), and individuals suffering from schizophrenia (M. A. Kim et al., 2010). Therefore, the suggested serial-to-parallel shift triggered by stress might also be a compensational mechanism. It appears that people who have problems in cognitive processing, regardless whether this is due to parallel affective processing, aging, or neuropsychological and psychiatric diseases, may be able to compensate these influences by an activation of other or further executive brain areas which processes facilitate/support superior cognitive processing.

At this point is has to be mentioned that the second study of this thesis revealed a differentiation between positive and negative affective influences (for a detailed discussion see section 5.5) and in combination with the behavioral findings of the first study (see section 4.4.2), it appears assumable that positive affective processing leads to inferior decision-making performance in a dual-task situation, while negative affective processing does not. This is in line with findings of studies investigating affective influences on decision making under risk (see section 3.4.2.2.2), but is in contrast to studies demonstrating that stress leads to disadvantageous decision under risk (see section 3.4.3.3.2). Such discrepancy might be explained by the dual-state theory of the dopamine system. The theory constitutes that the dopamine system characteristics change depending on whether or not the transmission at D1 or D2-receptors dominates (Durstewitz & Seamans, 2008; Seamans & Yang, 2004). For example, a highly activated D2-system enables multiple representations in

prefrontal networks and working memory, leading to increased processing capacity of these networks. While the D2-state is flexible and responsive, it is also susceptible to interferences. A D1-receptore dominated network is quite the opposite and therefore the capacities in such a network are more restricted (Durstewitz & Seamans, 2008; Seamans & Yang, 2004; Yildiz, Chmielewski, & Beste, 2013). Several studies have shown that reward and punishment are differentially associated with these systems: While reward processing is more likely mediated via the dopamine D1-receptor system, punishment processes are mediated by the D2-receptor system (e.g., Bromberg-Martin, Matsumoto, & Hikosaka, 2010; Ferguson et al., 2011; Hikida, Kimura, Wada, Funabiki, & Nakanishi, 2010; Kravitz, Tye, & Kreitzer, 2012; Schultz, Tremblay, & Hollerman, 2000). Transferring these findings to the results of the first and second study of the present thesis, it appears that a possible neural mechanisms underlying the differential influence of positive and negative affective processing on decision making under risk in a dual-tasking situation might also be attributed to the dopamine system: On one hand, stress or negative affective pictures may be comparable to an aversive condition like punishments and thus might lead to an increased activation of D2-receptors and a decreased activation of D1-receptors, which in turn triggers the assumed serial-to-parallel processing shift. On the other hand, assuming that the positive affective stimuli in the second study are comparable to a reward condition, may have led to an increased transmission of D1-receptors,which in turn led to decreased processing capacity and therefore to impaired decision-making performance. This assumption is in line with a study by Yildiz and colleagues (2013), who demonstrated a similar effect of reward and punishment on dual tasking: Compared to the CG, participants in the punishment group responded faster in the second task while participants of the reward group were slower. Moreover, the dual-state theory of dopamine might also explain the differential effect of stress on decision making under risk with (Pabst, Schoofs, et al., 2013) and without additional demand (Porcelli & Delgado, 2009; Putman, Antypa, et al., 2010; Starcke, et al., 2008): To perform a single task advantageously, tonic task shielding and a non-interference-prone state would be advantageously (Lehle, et al., 2009). If stress decreases the activation of D1-receptors and increases the transmission of D2-receptores, the activated state (vulnerable for interference) is not compatible with the demands of a single task. This would lead to the suggestion that dopamine might play a role in the suggested serial-to-parallel processing shift (see the beige ovals in Figure 22).

However, neither Yildiz and colleagues (2013) nor the studies of the present thesis investigated such involvement and there are some limitations to this interpretation that need to be mentioned: Even though stress increases the release of dopamine (Abercrombie, et al., 1989; Hutson, et al., 2004; Morrow, et al., 2000), and D2-receptors are more responsive to dopamine, which is accompanied by a modulation of baseline activity of neurons in the PFC, the exact role of D2-receptors in stress is quite unclear (Goto & Grace, 2005; Scornaiencki, Cantrup, Rushlow, & Rajakumar, 2009). While an increased binding to D2-receptors due to stress was found in monkeys (Tsukada, Ohba, Nishiyama, & Kakiuchi, 2011), this was not the case in young adults (Wand et al., 2007). Furthermore, the findings of neural activity in the first study of this thesis indicate an increased activation in the PFC in the SG compared to the CG, whereas the correlative analysis revealed a deactivation in the dlPFC within stressed participants. Regarding the aforementioned discussion this would indicate that there are more D2-receptors in the aPFC (higher transmission at D2-receptors than at D1-receptors during stress, see above) than in the dlPFC. But, studies investigating the differences in the distribution of D1- and D2-receptors found in particular differences in the striatum and the basal ganglia (e.g., Camps, Cortés, Gueye, Probst, & Palacios, 1989; Hall et al., 1994; Khan et al., 1998). So far, little is known about the differences in the distribution of D1-

and D2-receptors in the cortical parts of the PFC. Therefore, even though the involvement of dopamine is probably due to the fact that stress elicits dopamine (Abercrombie, et al., 1989; Hutson, et al., 2004; Morrow, et al., 2000), the application of the dual-system theory of dopamine to the results of the first and second study of the present thesis is rather limited. Future studies should investigate this process in more detail.

The following section will now give a general conclusion of the current findings and a perspective for future studies

7.3 General conclusion and perspective for future studies

The interaction between cognitive and affective processes in decision making under risk appears to be complex and depend on various situational and personal factors. In a simple decision situation (without additional affective and cognitive demands), cognitive processes dominate the decision-making process while affective processes are in particular relevant for the processing of (affective) feedback. The interaction in such simple situations might be seen in the point when the feedback information is evaluated, processed and integrated into the decision-making process (see sections 3, 3.1.2.2 and 3.2.2.2 for detailed information). The findings of the present thesis suggest that interaction become enlightening when further situational influences are present that cause additional affective or/and cognitive demand. Figure 22 displays the suggestions derived from the findings of the three studies of this thesis: In a stressful or affect-laden decision-making situation, in which an additional executive task has to be performed simultaneously, stressful or affective influences cause a neural activation shift which might be mediated by neurotransmitters such as dopamine. On one hand, this shift enables parallel task performance that retains decision-making performance. On the other hand, the shift is accompanied by an activation of higher-level executive functions. The higher-level executive functions (e.g., supervisory/monitoring function) in turn manage lower-level executive functions (e.g., categorization) and facilitate the performance of the two tasks in parallel (i.e., assumed mediation effect). This retains superior decision-making performance. Moreover, executive functions may also moderate the effect of affective influences on decision-making behavior (i.e., assumed moderation effect).

In connection with the example from the beginning of the thesis (see section 2), it is assumable that the student who is delayed on his/her way for an important exam at the university (i.e., he/she might be stressed) may still be able to manage the situation and consider all important information (e.g., arriving time of the next train, duration time of the trip to university, starting time of the exam) to make a rational decision. This is possible due to the neural activation shift, which initiates the involvement of (executive) processes supporting the decision-making processes leading to an advantageous decision. However, there might be some inter-individual differences as well as situational factors which influence the extent of performance.

Considering the model in Figure 22, it can be assumed that the degree of the interaction between cognitive and affective processes in decision making in demanding situations probably depends on several situational and individual factors. For example, it appears to depend on the cognitive ability of a person. As shown in the second study of the present thesis (see section 5), only participants with superior executive functions were unaffected by the affective influences and demonstrated advantageous decision-making behavior. Additionally, as postulated by Starcke and Brand (2012) there might be a variety of mediators and moderators affecting the influence of stress on decision making, which might be relevant for the model assumed in Figure 22. For example, demographical data such as gender or age: While various studies demonstrated

differential decision-making performance in men and women (see section 3.4.3.3.2) during stress, the interaction between age and stress, as well as between age and cognitive functions, is attributed to volume reduction of prefrontal brain regions, which might influence task performance (Cabeza, 2001; Raz, 2000). Furthermore, higher age is associated with decreased effectiveness of dopamine transmission (Volkow et al., 2000), which might possibly influence the reaction to stress and affective influences (see discussion in section 7.2) and therefore the performance in a decision-making situation with additional affective and cognitive load. Besides these factors strategy application and sensitivity to reward or punishment might also affect the influence of stress or affective influences in general on decision making (Starcke & Brand, 2012). For example, as discussed in section 3.4.2.2, certain decision strategies are more compatible with a certain affective state than others and thus the individual preference for a decision strategy might interfere with the affective influence in this kind of demanding decision situations. Regarding reward/punishment sensitivity, it was found that in highly punishment sensitive subjects, increasing of negative affect was associated with superior punishment learning accuracy, while it was inversely related in less sensitive subjects (Cavanagh, Frank, & Allen, 2011). Furthermore, it is conceivable that whether or not a situation offers coping strategies, like affect-regulation, or whether a person applies them or not, determines the decision-making performance in such demanding situations. Heilman and colleagues (2010) demonstrated that participants applying diverse affect-regulation strategies display different decision-making performance: Participants in a negative affective state who applied cognitive reappraisal as an regulation strategy demonstrated increased risk-seeking compared to participants who used expressive suppression or no affect- regulation strategy (for detailed information about the findings see section 3.4.2.2.2). Thus, it appears that the decision-making performance in a situation with additional affective and cognitive demand depends on various situational and personal factors and therefore might differ between individuals. However, in general, humans may be able to still decide advantageously in these kinds of demanding situations, due to the interaction between affective and cognitive processes.

7.3.1 Practical application

Some of the aforementioned aspects that might influence decision-making performance in demanding situations provide an opportunity to intervene in order to support individuals who show deficits in facets necessary for superior decision-making performance in this situations, for example cognitive functions. Recent studies have shown that in particular cognitive functions involved in dual tasking, such as executive control and coordination skills, are trainable in elderly people (Bherer, et al., 2005; Bherer et al., 2008; Lussier, Gagnon, & Bherer, 2012) as well as kids with ADHD (Kray, Karbach, Haenig, & Freitag, 2012). Thus, it might be of special interest to figure out which specific cognitive functions are involved in decision situations with additional demand (see Figure 22). These kind of situations often occur in everyday life and might be challenging for people suffering from cognitive impairments like older people or people with prefrontal dysfunctions or neurological and psychiatric diseases, since it was shown that such individuals show deficits in for example, dual-tasking (Allen et al., 2002; Baddeley, et al., 1997; Hartley & Little, 1999) executive functioning (Belleville, et al., 2006; Collette, Van der Linden, & Salmon, 1999; Elliott, 2003), and decision making (Brand & Schiebener, 2013; Euteneuer, et al., 2009; Rogers, Everitt, et al., 1999; Zamarian, et al., 2010). Knowledge about the specific cognitive functions involved in these processes would therefore facilitate the development of apposite trainings. These trainings would increase the probability that individuals with cognitive deficits would be able to handle

demanding everyday life situations. Moreover, it was shown that maintaining good cognitive functions is essential to functional independence and quality of life (Depp, Vahia, & Jeste, 2010), particularly in older people.

However, whether or not the benefits from these trainings are also transferable to other cognitive functions or tasks is still under debate: Kray and Karbach (2009) demonstrated that dual-tasking or rather task-switching trainings are transferable to structural dissimilar executive tasks and fluid intelligence in young and older adults. In contrast, Strobach, Frensch, Soutscheck, and Schubert (2012) found that coordination skills are less transferable to new situations because they are rather task-specific. Therefore, the question remains, whether a cognitive training for the executive functions found to be involved in decision making with an additional executive load (i.e., monitoring), would be effective after all. Strobach and colleagues argued that the training situations in the two studies mentioned above might not have been comparable: While participants in the study by Karbach and Kray (2009) got information about the tasks and the sequence of the task before performing the switching task, participants in the study by Strobach and colleagues (2012) performed the tasks depending on the stimulus presented (i.e., visual stimuli indicated visual task, auditory stimuli indicated auditory task). Strobach and colleagues argue that the maintenance and coordination of the task sequence in the study by Karbach and Kray (2009) may have enhanced processes which enable transfer to structural dissimilar task situations. This would be in line with recent findings indicating that transfer effects improve if the training taps into higher-level executive functioning rather than basic processing or specific strategies (Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Noack, Lövdén, Schmiedek, & Lindenberger, 2009). Since, the third study of the present thesis revealed the involvement of higher-level executive functions; it seems likely that a cognitive training would be effectively. Hence, the aim for future studies should be the development and evaluation of a cognitive training which includes in particular higher-level executive functions required for advantageous decision making in a situation with additional cognitive load. This would probably enhance the transfer to for example, real life decision-making situations with additional demand.

Moreover, there is evidence that cognitive training results in increased plasticity of the associated brain regions (for an overview see Jones et al., 2006; Kelly & Garavan, 2005; Klingberg, 2010), which indicates a consolidation on neural level: While learning how to juggle leads to an increase in grey matter (Draganski et al., 2004), cognitive trainings such as working memory trainings lead to a functional plasticity of the brain, meaning increased activation of the involved areas (Olesen, Westerberg, & Klingberg, 2004). Therefore, a cognitive training of the higher-level executive functions would possibly lead to an increased activity in the dlPFC and/or the aPFC after training. These are areas that are known to be involved during stress reactions (see section 3.4.3.1) and are also involved in affective processing (see section 3.1.1). The question remains whether such neural changes would lead to alterations of the effect of stress and affective influences on cognitive functions associated with these areas (e.g., executive functions, decision making under risk). Future studies should investigate this in more detail. However, it has to be mentioned that the permanency of the plasticity changes has to be questioned. Draganski and colleagues (2004) for example, found that the induced expansion of the grey matter following training decreased after a training-free interval of three month. Furthermore, this research field is at an early stage and more studies are needed to make a meaningful statement.

Another aspect that might give an answer to the previous question refers to the catecholamine dopamine, which is modulated by cognitive trainings (for a short overview see Klingberg, 2010). In a recent

study it was demonstrated that after a working memory training of five weeks the working memory capacity was significantly increased and correlated with changes in cortical D1 receptors, mostly because of a decrease of the density of D1-receptors (McNab et al., 2009). If cognitive training influences the catecholamine dopamine in a way that it affects the density of the receptors, trainings might also have a preventive quality: As mentioned above dopamine may also be involved in positive affect such as reward (Yildiz, et al., 2013) by increasing the transmission at D1-receptors, which in turn might lead to disadvantageous decision making in a dual-tasking situation (for detailed information see section 7.2). A decrease of the density of these receptors due to cognitive training of the involved executive functions might prevent such increasing transmission and prevent inferior decision-making performance. However, this assumption is preliminary since the causality of the findings by McNab and colleagues (2009) is not very clear (see Klingberg, 2010 for a detailed discussion) and neither is the role of the distribution of the dopamine receptors in the PFC. Therefore, the exact role of dopamine in decision making under affective influence remains unclear.

7.3.2 The end

Overall, the three studies of the present thesis extend the knowledge about the interaction between cognitive and affective processes in decision making in demanding situations and about the underlying neural correlates: It appears that an additional cognitive and affective demand in decision-making situations triggers a neural activation shift which enables parallel processing and activates higher-level executive functions, which again facilitate the decision-making performance. However, the impact of certain situational and personal factors, such as the application of affect-regulation strategies and demographic variables, are still unknown. Moreover, the role of dopamine in these processes is unclear. Future studies should consider the role of dopamine in decision making under risk, in affective processes and cognitive trainings and the possible resulting interaction in more detail. Hereby, it appears advisable to use functional and effective connectivity analysis: This might not only bring order into the differential findings of the influence of training on neural plasticity (Kelly & Garavan, 2005), but might also be helpful in investigating the neural network underlying the interaction between decision making, affective, and cognitive processes, more detailed. Instead of comparing the neural activity differences of one single brain region before an intervention compared to after an intervention, this analysis considers the connectivity of one brain region to other brain regions and the changes in these activation patterns due to the intervention (for detailed information about this analysis see Büchel & Friston, 2000; Friston, 2002; McIntosh, 1998, 1999; McIntosh & Gonzalez-Lima, 1994). This might give more insights into how the brain manages the compensational mechanisms like the serial-to-parallel shift in demanding decision-making situations. Outcomes from such studies might be promising and increase the knowledge about any issues in the brain functions of individuals who demonstrate disadvantageous decision making under risk in diverse situations. This knowledge might then be used to create corresponding and apposite interventions.

Thus, from applied and neuropsychological perspective, the role of the interaction between underlying affective and cognitive processes for decision making in demanding situations, is and will stay an interesting and promising field of research with high relevance.

8. References

Abercrombie, E. D., Keefe, K. A., DiFrischia, D. S., & Zigmond, M. J. (1989). Differential effect of stress on in vivo dopamine release in striatum, nucleus accumbens, and medial frontal cortex. *Journal of Neurochemistry, 52*, 1655–1658. doi: 10.1111/j.1471-4159.1989.tb09224.x

Adcock, R. A., Constable, R. T., Gore, J. C., & Goldman-Rakic, P. S. (2000). Functional neuroanatomy of executive processes involved in dual-task performance. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 3567–3572. doi: 10.1073/pnas.97.7.3567

Adida, M., Clark, L., Pomietto, P., Kaladjian, A., Besnier, N., Azorin, J.-M., . . . Jeanningros, R. (2008). Lack of insight may predict impaired decision making in manic patients. *Bipolar Disorders, 10*, 829–837. doi: 10.1111/j.1399-5618.2008.00618.x

Åhs, F., Furmark, T., Michelgård, Å., Långström, B., Appel, L., Wolf, O. T., . . . Fredrikson, M. (2006). Hypothalamic blood flow correlates positively with stress-induced cortisol levels in subjects with social anxiety disorder. *Psychosomatic Medicine, 68*, 859–862. doi: 10.1097/01.psy.0000242120.91030.d8

Alexander, G. E., DeLong, M. R., & Strick, P. L. (1986). Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annual Review of Neuroscience, 9*, 357–381. doi: 10.1146/annurev.ne.09.030186.002041

Alhakami, A. S., & Slovic, P. (1994). A psychological study of the inverse relationship between perceived risk and perceived benefit. *Risk Analysis, 14*, 1085–1096. doi: 10.1111/j.1539-6924.1994.tb00080.x

Allen, P. A., Mei-Ching, L., Murphy, M. D., Sanders, R. E., Judge, K. S., & McCann, R. S. (2002). Age differences in overlapping-task performance: Evidence for efficient parallel processing in older adults. *Psychology and Aging, 17*, 505–519. doi: 10.1037/0882-7974.17.3.505

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Mascovitch (Eds.), *Conscious and nonconscious information processing: Attention and performance XV* (pp. 421-452). Cambridge, MA: MIT Press.

Altmann, E. M., & Gray, W. D. (2008). An integrated model of cognitive control in task switching. *Psychological Review, 115*, 602–639. doi: 10.1037/0033-295x.115.3.602

Alvarez, J. A., & Emory, E. (2006). Executive function and the frontal lobes: A meta-analytic review. *Neuropsychology Review, 16*, 17–42. doi: 10.1007/s11065-006-9002-x

Anderson, A. K., & Phelps, E. A. (2001). Lesions of the human amygdala impair enhanced perception of emotionally salient events. *Nature, 411*, 305–309. doi: 10.1038/35077083

Arbuthnott, K., & Frank, J. (2000). Executive control in set switching: Residual switch cost and task-set inhibition. *Canadian Journal of Experimental Psychology, 54*, 33–41. doi: 10.1037/h0087328

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience, 10*, 410–422. doi: 10.1038/nrn2648

Arnsten, A. F. T., & Goldman-Rakic, P. S. (1998). Noise stress impairs prefrontal cortical cognitive function in monkeys: Evidence for a hyperdopaminergic mechanism. *Archives of General Psychiatry, 55*, 362–368. doi: 10.1001/archpsyc.55.4.362

Aron, A. R., Monsell, S., Sahakian, B. J., & Robbins, T. W. (2004). A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. *Brain, 127*, 1561–1573. doi: 10.1093/brain/awh169

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science, 15*, 610–615. doi: 10.2307/40064149

Arrington, C. M., & Yates, M. M. (2009). The role of attentional networks in voluntary task switching. *Psychonomic Bulletin and Review, 16*, 660–665. doi: 10.3758/pbr.16.4.660

Awh, E., Jonides, J., Smith, E. E., Schumacher, E. H., Koeppe, R. A., & Katz, S. (1996). Dissociation of storage and rehearsal in verbal working memory: Evidence from positron emission tomography. *Psychological Science, 7*, 25–31. doi: 10.2307/40062903

Baddeley, A. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 49*, 5–28. doi: 10.1080/713755608

Baddeley, A. (1998a). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 51*, 819–852. doi: 10.1080/713755788

Baddeley, A. (1998b). Working memory. *Science, 321*, 167–173. doi: 10.1016/S0764-4469(97)89817-4

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423. doi: 10.1016/S1364-6613(00)01538-2

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews. Neuroscience, 4*, 829–839. doi: 10.1038/nrn1201

Baddeley, A. (2010). Working memory. *Current Biology, 20*, R136–R140. doi: 10.1016/j.cub.2009.12.014

Baddeley, A., & Della Sala, S. (1996). Working memory and executive control. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 351*, 1397–1404. doi: 10.1098/rstb.1996.0123

Baddeley, A., Della Sala, S., Papagno, C., & Spinnler, H. (1997). Dual-task performance in dysexecutive and nondysexecutive patients with a frontal lesion. *Neuropsychology, 11*, 187–194. doi: 10.1037/0894-4105.11.2.187

Baddeley, A., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-89). New York, NY: Academic Press.

Baddeley, A., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory. Mechanisms of active maintenance and executive control* (pp. 28-61). Cambridge, UK: Cambridge University Press.

Bagneux, V., Bollon, T., & Dantzer, C. (2012). Do (un)certainty appraisal tendencies reverse the influence of emotions on risk taking in sequential tasks? *Cognition and Emotion, 26*, 568–576. doi: 10.1080/02699931.2011.602237

Baier, B., Karnath, H.-O., Dieterich, M., Birklein, F., Heinze, C., & Müller, N. G. (2010). Keeping memory clear and stable - The contribution of human basal ganglia and prefrontal cortex to working memory. *Journal of Neuroscience, 30*, 9788–9792. doi: 10.1523/jneurosci.1513-10.2010

Bandettini, P. A., Birn, R. M., & Donahue, K. M. (2000). Functional MRI: Background, methodology, limits, and implementation. In J. T. Cacioppo, L. G. Tassinary & G. G. Bernston (Eds.), *Handbook of psychophysiology* (pp. 978-1014). New York, NY: Cambridge University Press

Bandettini, P. A., Wong, E. C., Hinks, R. S., Tikofsky, R. S., & Hyde, J. S. (1992). Time course EPI of human brain function during task activation. *Magnetic Resonance in Medicine, 25*, 390–397. doi: 10.1002/mrm.1910250220

Bangen, K. J., Kaup, A. R., Mirzakhanian, H., Wierenga, C. E., Jeste, D. V., & Eyler, L. T. (2012). Compensatory brain activity during encoding among older adults with better recognition memory for face-name pairs: An integrative functional, structural, and perfusion imaging study. *Journal of the International Neuropsychological Society, 18*, 402–413. doi: 10.1017/S1355617712000197

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*, 65–94. doi: 10.1037/0033-2909.121.1.65

Baron, R. M., & Kenny, D. A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51*, 1173–1182.

Barry, D., & Petry, N. M. (2008). Predictors of decision-making on the Iowa Gambling Task: Independent effects of lifetime history of substance use disorders and performance on the Trail Making Test. *Brain and Cognition, 66*, 243–252. doi: 10.1016/j.bandc.2007.09.001

Bäumler, G. (1985). *Farbe-Wort-Interferenztest nach Stroop (FWIT) [Color-Word-Interference-Test adapted from Stroop]*. Göttingen, Germany: Hogrefe.

Bayard, S., Abril, B., Yu, H., Scholz, S., Carlander, B., & Dauvilliers, Y. (2011). Decision making in narcolepsy with cataplexy. *Sleep, 34*, 99–104.

Bayard, S., Raffard, S., & Gely-Nargeot, M.-C. (2011). Do facets of self-reported impulsivity predict decision-making under ambiguity and risk? Evidence from a community sample. *Psychiatry Research, 190*, 322–326. doi: 10.1016/j.psychres.2011.06.013

Bazanis, E., Rogers, R. D., Dowson, J. H., Taylor, P., Meux, C., Staley, C., . . . Sahakian, B. J. (2002). Neurocognitive deficits in decision-making and planning of patients with DSM-III-R borderline personality disorder. *Psychological Medicine, 32*, 1395–1405. doi: 10.1017/S0033291702006657

Bechara, A., & Damasio, A. R. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior, 52*, 336–372. doi: 10.1016/j.geb.2004.06.010

Bechara, A., Damasio, A. R., Damasio, H., & Anderson, S. W. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition, 50*, 7–15. doi: 10.1016/0010-0277(94)90018-3

Bechara, A., & Damasio, H. (2002). Decision-making and addiction (part I): Impaired activation of somatic states in substance dependent individuals when pondering decisions with negative future consequences. *Neuropsychologia, 40*, 1675–1689. doi: 10.1016/S0028-3932(02)00015-5

Bechara, A., Damasio, H., & Damasio, A. R. (2000). Emotion, decision making and the orbitofrontal cortex. *Cerebral Cortex, 10*, 295–307. doi: 10.1093/cercor/10.3.295

Bechara, A., Damasio, H., Damasio, A. R., & Lee, G. P. (1999). Different contributions of the human amygdala and ventromedial prefrontal cortex to decision-making. *Journal of Neuroscience, 19*, 5473–5481.

Bechara, A., Damasio, H., Tranel, D., & Anderson, S. W. (1998). Dissociation of working memory from decision making within the human prefrontal cortex. *Journal of Neuroscience, 18*, 428–437.

Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (1997). Deciding advantageously before knowing the advantageous strategy. *Science, 275*, 1293–1295. doi: 10.1126/science.275.5304.1293

Bechara, A., Dolan, S., Denburg, N., Hindes, A., Anderson, S. W., & Nathan, P. E. (2001). Decision-making deficits, linked to a dysfunctional ventromedial prefrontal cortex, revealed in alcohol and stimulant abusers. *Neuropsychologia, 39*, 376–389. doi: 10.1016/S0028-3932(00)00136-6

Bechara, A., & Martin, E. M. (2004). Impaired decision making related to working memory deficits in individuals with substance addictions. *Neuropsychology, 18*, 152–162. doi: 10.1037/0894-4105.18.1.152

Bechara, A., Tranel, D., & Damasio, H. (2000). Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions. *Brain, 123*, 2189–2202. doi: 10.1093/brain/123.11.2189

Bechara, A., Tranel, D., Damasio, H., & Damasio, A. R. (1996). Failure to respond autonomically to anticipated future outcomes following damage to prefrontal cortex. *Cerebral Cortex, 6*, 215–225. doi: 10.1093/cercor/6.2.215

Belleville, S., Rouleau, N., & Van der Linden, M. (2006). Use of the Hayling task to measure inhibition of prepotent responses in normal aging and Alzheimer's disease. *Brain and Cognition, 62*, 113–119. doi: 10.1016/j.bandc.2006.04.006

Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *Journal of General Psychology, 39*, 15–22.

Beste, C., Yildiz, A., Meissner, T. W., & Wolf, O. T. (2013). Stress improves task processing efficiency in dual-tasks. *Behavioural Brain Research, 252*, 260–265. doi: 10.1016/j.bbr.2013.06.013

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: Are there age-related differences in plasticity of attentional control? *Psychology and Aging, 20*, 695–709. doi: 10.1037/0882-7974.20.4.695

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: Further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental Aging Research, 34*, 188–219. doi: 10.1080/03610730802070068

Bigelow, H. J. (1850). Dr. Harlow's case of recovery from the passage of an iron bar through the head. *American Journal of the Medical Sciences, 16*, 13–22.

Bless, H., & Schwarz, N. (1999). Sufficient and necessary conditions in dual-process models: The case of mood and information processing. In S. Chaiken & Y. Trope (Eds.), *Dual-process theories in social psychology* (pp. 423-440). New York, NY: Guilford Press.

Bogg, T., Fukunaga, R., Finn, P. R., & Brown, J. W. (2012). Cognitive control links alcohol use, trait disinhibition, and reduced cognitive capacity: Evidence for medial prefrontal cortex dysregulation during reward-seeking behavior. *Drug and Alcohol Dependence, 122*, 112–118. doi: 10.1016/j.drugalcdep.2011.09.018

Bolla, K. I., Eldreth, D. A., Matochik, J. A., & Cadet, J. L. (2005). Neural substrates of faulty decision-making in abstinent marijuana users. *NeuroImage, 26*, 480–492. doi: 10.1016/j.neuroimage.2005.02.012

Bonatti, E., Kuchukhidze, G., Zamarian, L., Trinka, E., Bodner, T., Benke, T., & Delazer, M. (2009). Decision making in ambiguous and risky situations after unilateral temporal lobe epilepsy surgery. *Epilepsy and Behavior, 14*, 665–673. doi: 10.1016/j.yebeh.2009.02.015

Bonatti, E., Zamarian, L., Wagner, M., Benke, T., Hollosi, P., Strubreither, W., & Delazer, M. (2008). Making decisions and advising decisions in traumatic brain injury. *Cognitive and Behavioral Neurology, 21*, 164–175. doi: 10.1097/WNN.0b013e318184e688

Boucsein, W. (1992). *Electrodermal activity*. New York, NY: Plenum Press.

Bouscein, W. (1988). *Elektrodermale Aktivität. Grundlagen, Methoden und Anwendungen [Electrodermal activity. Basics, methods, and application]*. Berlin, Germany: Springer-Verlag.

Brand, M. (2008). Does the feedback from previous trials influence current decisions? A study on the role of feedback processing in making decisions under explicit risk conditions. *Journal of Neuropsychology, 2*, 431–443. doi: 10.1348/174866407X220607

Brand, M., Franke-Sievert, C., Jacoby, G. E., Markowitsch, H. J., & Tuschen-Caffier, B. (2007). Neuropsychological correlates of decision making in patients with bulimia nervosa. *Neuropsychology, 21*, 742–750. doi: 10.1037/0894-4105.21.6.742

Brand, M., Fujiwara, E., Borsutzky, S., Kalbe, E., Kessler, J., & Markowitsch, H. J. (2005). Decision-making deficits of Korsakoff patients in a new gambling task with explicit rules: Associations with executive functions. *Neuropsychology, 19*, 267–277. doi: 10.1037/0894-4105.19.3.267

Brand, M., Grabenhorst, F., Starcke, K., Vandekerckhove, M. M. P., & Markowitsch, H. J. (2007). Role of the amygdala in decisions under ambiguity and decisions under risk: Evidence from patients with Urbach-Wiethe disease. *Neuropsychologia, 45*, 1305–1317. doi: 10.1016/j.neuropsychologia.2006.09.021

Brand, M., Heinze, K., Labudda, K., & Markowitsch, H. J. (2008). The role of strategies in deciding advantageously in ambiguous and risky situations. *Cognitive Processing, 9*, 159–173. doi: 10.1007/s10339-008-0204-4

Brand, M., Kalbe, E., Labudda, K., Fujiwara, E., Kessler, J., & Markowitsch, H. J. (2005). Decision-making impairments in patients with pathological gambling. *Psychiatry Research, 133*, 91–99. doi: 10.1016/j.psychres.2004.10.003

Brand, M., Labudda, K., Kalbe, E., Hilker, R., Emmans, D., Fuchs, G., . . . Markowitsch, H. J. (2004). Decision-making impairments in patients with Parkinson's disease. *Behavioural Neurology, 15*, 77–85.

Brand, M., Labudda, K., & Markowitsch, H. J. (2006). Neuropsychological correlates of decision-making in ambiguous and risky situations. *Neural Networks, 19*, 1266–1276. doi: 10.1016/j.neunet.2006.03.001

Brand, M., Laier, C., Pawlikowski, M., & Markowitsch, H. J. (2009). Decision making with and without feedback: The role of intelligence, strategies, executive functions, and cognitive styles. *Journal of Clinical and Experimental Neuropsychology, 31*, 984–998. doi: 10.1080/13803390902776860

Brand, M., Pawlikowski, M., Labudda, K., Laier, C., Rothkirch, N., & Markowitsch, H. J. (2009). Do amnesic patients with Korsakoff's syndrome use feedback when making decisions under risky conditions? An experimental investigation with the Game of Dice Task with and without feedback. *Brain and Cognition, 69*, 279–290. doi: 10.1016/j.bandc.2008.08.003

Brand, M., Recknor, E. C., Grabenhorst, F., & Bechara, A. (2007). Decisions under ambiguity and decisions under risk: Correlations with executive functions and comparisons of two different gambling tasks with implicit and explicit rules. *Journal of Clinical and Experimental Neuropsychology, 29*, 86–99. doi: 10.1080/13803390500507196

Brand, M., Roth-Bauer, M., Driessen, M., & Markowitsch, H. J. (2008). Executive functions and risky decision-making in patients with opiate dependence. *Drug and Alcohol Dependence, 97*, 64–72. doi: 10.1016/j.drugalcdep.2008.03.017

Brand, M., & Schiebener, J. (2013). Interactions of age and cognitive functions in predicting decision making under risky conditions over the life span. *Journal of Clinical and Experimental Neuropsychology, 35*, 9–23. doi: 10.1080/13803395.2012.740000

Brass, M., Ullsperger, M., Knoesche, T. R., von Cramon, D. Y., & Phillips, N. A. (2005). Who comes first? The role of the prefrontal and parietal cortex in cognitive control. *Journal of Cognitive Neuroscience, 17*, 1367–1375. doi: 10.1162/0898929054985400

Brett, M. (1999). The MNI brain and the Talairach atlas, from http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach

Broadbent, D. E. (1958). *Perception and communication*. Elmsford, NY: Pergamon Press.

Bromberg-Martin, E. S., Matsumoto, M., & Hikosaka, O. (2010). Dopamine in motivational control: Rewarding, aversive, and alerting. *Neuron, 68*, 815–834. doi: 10.1016/j.neuron.2010.11.022

Brown, J. (1958). Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology, 10*, 12–21. doi: 10.1080/17470215808416249

Büchel, C., & Friston, K. J. (2000). Assessing interactions among neuronal systems using functional neuroimaging. *Neural Networks, 13*, 871–882. doi: 10.1016/S0893-6080(00)00066-6

Büchel, C., Morris, J., Dolan, R. J., & Friston, K. J. (1998). Brain systems mediating aversive conditioning: An event-related fMRI study. *Neuron, 20*, 947–957. doi: 10.1016/S0896-6273(00)80476-6

Buelow, M. T., & Suhr, J. A. (2009). Construct validity of the Iowa Gambling Task. *Neuropsychology Review, 19*, 102–114. doi: 10.1007/s11065-009-9083-4

Bunge, S. A., Klingberg, T., Jacobsen, R. B., & Gabrieli, J. D. E. (2000). A resource model of the neural basis of executive working memory. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 3573–3578. doi: 10.1073/pnas.97.7.3573

Burgess, P. W., Alderman, N., Evans, J., Emslie, H., & Wilson, B. A. (1998). The ecological validity of tests of executive function. *Journal of the International Neuropsychological Society, 4*, 547–558.

Burgess, P. W., & Shallice, T. (1996). Response suppression, initiation and strategy use following frontal lobe lesions. *Neuropsychologia, 34*, 263–272. doi: 10.1016/0028-3932(95)00104-2

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4*, 215–222. doi: 10.1016/S1364-6613(00)01483-2

Butler, K. M., Arrington, C. M., & Weywadt, C. (2011). Working memory capacity modulates task performance but has little influence on task choice. *Memory and Cognition, 39*, 708–724. doi: 10.3758/s13421-010-0055-y

Cabeza, R. (2001). Functional neuroimaging of cognitive aging. In R. Cabeza & A. Kingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 331-377). Cambridge, MA: MIT Press.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*, 85–100. doi: 10.1037/0882-7974.17.1.85

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. *NeuroImage, 17*, 1394–1402. doi: 10.1006/nimg.2002.1280

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex, 14*, 364–375. doi: 10.1093/cercor/bhg133

Cabeza, R., Dolcos, F., Graham, R., & Nyberg, L. (2002). Similarities and differences in the neural correlates of episodic memory retrieval and working memory. *NeuroImage, 16*, 317–330. doi: 10.1006/nimg.2002.1063

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12*, 1–47. doi: 10.1162/08989290051137585

Cahill, L., Haier, R. J., Fallon, J., Alkire, M. T., Tang, C., Keator, D., . . . McGaugh, J. L. (1996). Amygdala activity at encoding correlated with long-term, free recall of emotional information. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 8016–8021.

Callicott, J. H., Mattay, V. S., Bertolino, A., Finn, K., Coppola, R., Frank, J. A., . . . Weinberger, D. R. (1999). Physiological characteristics of capacity constraints in working memory as revealed by functional MRI. *Cerebral Cortex, 9*, 20–26. doi: 10.1093/cercor/9.1.20

Campbell, M. C., Stout, J. C., & Finn, P. R. (2004). Reduced autonomic responsiveness to gambling task losses in Huntington's disease. *Journal of the International Neuropsychological Society, 10*, 239–245. doi: 10.1017/S1355617704102105

Camps, M., Cortés, R., Gueye, B., Probst, A., & Palacios, J. M. (1989). Dopamine receptors in human brain: Autoradiographic distribution of D2 sites. *Neuroscience, 28*, 275–290. doi: 10.1016/0306-4522(89)90179-6

Canli, T., Zhao, Z., Brewer, J., Gabrieli, J. D. E., & Cahill, L. (2000). Event-related activation in the human amygdala associates with later memory for individual emotional experience. *Journal of Neuroscience, 20*, RC99.

Cannon, W. B. (1914). The emergency function of the adrenal medulla in pain and the major emotions. *American Journal of Physiology, 33*, 356–372.

Cannon, W. B. (1927). The James-Lange theory of emotions: A critical examination and an alternative theory. *American Journal of Psychology, 39*, 106–124. doi: 10.2307/1415404

Cannon, W. B. (1931). Against the James–Lange and the thalamic theories of emotions. *Psychological Review, 38*, 281–295. doi: 10.1037/h0072957

Cassotti, M., Habib, M., Poirel, N., Aïte, A., Houdé, O., & Moutier, S. (2012). Positive emotional context eliminates the framing effect in decision-making. *Emotion, 12*, 926–931. doi: 10.1037/a0026788

Cavanagh, J. F., Frank, M. J., & Allen, J. J. B. (2011). Social stress reactivity alters reward and punishment learning. *Social Cognitive and Affective Neuroscience, 6*, 311–320. doi: 10.1093/scan/nsq041

Chan, R. C. K., Shum, D., Toulopoulou, T., & Chen, E. Y. H. (2008). Assessment of executive functions: Review of instruments and identification of critical issues. *Archives of Clinical Neuropsychology, 23*, 201–216. doi: 10.1016/j.acn.2007.08.010

Chanraud, S., Pitel, A.-L., Müller-Oehring, E. M., Pfefferbaum, A., & Sullivan, E. V. (2013). Remapping the brain to compensate for impairment in recovering alcoholics. *Cerebral Cortex, 23*, 97–104. doi: 10.1093/cercor/bhr381

Cheung, E., & Mikels, J. A. (2011). I'm feeling lucky: The relationship between affect and risk-seeking in the framing effect. *Emotion, 11*, 852–859. doi: 10.1037/a0022854

Chrousos, G. P., & Gold, P. W. (1992). The concepts of stress and stress system disorders. *JAMA: Journal of the American Medical Association, 267*, 1244–1252. doi: 10.1001/jama.1992.03480090092034

Clark, L., Bechara, A., Damasio, H., Aitken, M. R. F., Sahakian, B. J., & Robbins, T. W. (2008). Differential effects of insular and ventromedial prefrontal cortex lesions on risky decision-making. *Brain, 131*, 1311–1322. doi: 10.1093/brain/awn066

Clark, L., Li, R., Wright, C. M., Rome, F., Fairchild, G., Dunn, B. D., & Aitken, M. R. F. (2012). Risk-avoidant decision making increased by threat of electric shock. *Psychophysiology, 49*, 1436–1443. doi: 10.1111/j.1469-8986.2012.01454.x

Clore, G. L., Schwarz, N., & Conway, M. (1994). Affective causes and consequences of social information processing. In R. S. Wyer & T. K. Srull (Eds.), *Handbook of social cognition* (2nd ed., Vol. 1, pp. 323-418). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*, 155–159.

Cohen, J., Cohen, P., Aiken, L. S., & West, S. G. (2003). *Applied multiple regression, correlation analysis for the behavioral sciences* (3 ed.). London, UK: Lawrence Erlbaum Associates.

Cohen, J. D., Perlstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., & Smith, E. E. (1997). Temporal dynamics of brain activation during a working memory task. *Nature, 386*, 604–608. doi: 10.1038/386604a0

Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience and Biobehavioral Reviews, 26*, 105–125. doi: 10.1016/S0149-7634(01)00063-X

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping, 25*, 409–423. doi: 10.1002/hbm.20118

Collette, F., Van der Linden, M., & Salmon, E. (1999). Executive dysfunction in Alzheimer's disease. *Cortex, 35*, 57–72. doi: 10.1016/S0010-9452(08)70785-8

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin and Review, 12*, 769–786. doi: 10.3758/bf03196772

Cools, R., Gibbs, S. E., Miyakawa, A., Jagust, W., & D'Esposito, M. (2008). Working memory capacity predicts dopamine synthesis capacity in the human striatum. *Journal of Neuroscience, 28*, 1208–1212. doi: 10.1523/jneurosci.4475-07.2008

Cooper, R. P., Wutke, K., & Davelaar, E. J. (2012). Differential contributions of set-shifting and monitoring to dual-task interference. *Quarterly Journal of Experimental Psychology, 65*, 587–612. doi: 10.1080/17470218.2011.629053

Cousijn, H., Rijpkema, M., Qin, S., van Wingen, G. A., & Fernández, G. (2012). Phasic deactivation of the medial temporal lobe enables working memory processing under stress. *NeuroImage, 59*, 1161–1167. doi: 10.1016/j.neuroimage.2011.09.027

Critchley, H. D., Corfield, D. R., Chandler, M. P., Mathias, C. J., & Dolan, R. J. (2000). Cerebral correlates of autonomic cardiovascular arousal: A functional neuroimaging investigation in humans. *Journal of Physiology, 523*, 259–270. doi: 10.1111/j.1469-7793.2000.t01-1-00259.x

Cummings, J. L. (1995). Anatomic and behavioral aspects of frontal-subcortical circuitsa. *Annals of the New York Academy of Sciences, 769*, 1–14. doi: 10.1111/j.1749-6632.1995.tb38127.x

D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature, 378*, 279–281. doi: 10.1038/378279a0

Dalrymple-Alford, J. C., Kalders, A. S., Jones, R. D., & Watson, R. W. (1994). A central executive deficit in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 57*, 360–367.

Damasio, A. R. (1989a). The brain binds entities and events by multiregional activation from convergence zones. *Neural Computation, 1*, 123–132. doi: 10.1162/neco.1989.1.1.123

Damasio, A. R. (1989b). Time-locked multiregional retroactivation: A systems-level proposal for the neural substrates of recall and recognition. *Cognition, 33*, 25–62. doi: 10.1016/0010-0277%2889%2990005-X

Damasio, A. R. (1994). *Descartes' error*. New York, NY: Putnam.

Damasio, A. R., Everitt, B. J., & Bishop, D. (1996). The somatic marker hypothesis and the possible functions of the prefrontal cortex. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 351*, 1413–1420. doi: 10.1098/rstb.1996.0125

Damasio, A. R., Grabowski, T. J., Bechara, A., Damasio, H., Ponto, L. L. B., Parvizi, J., & Hichwa, R. D. (2000). Subcortical and cortical brain activity during the feeling of self-generated emotions. *Nature Neuroscience, 3*, 1049–1156. doi: 10.1038/79871

Damasio, A. R., Tranel, D., & Damasio, H. (1990). Individuals with sociopathic behavior caused by frontal damage fail to respond autonomically to social stimuli. *Behavioural Brain Research, 41*, 81–94. doi: 10.1016/0166-4328(90)90144-4

Damasio, A. R., Tranel, D., & Damasio, H. (1991). Somatic markers and the guidance of behavior. In H. S. Levin (Ed.), *Frontal Lobe Function and Dysfunction* (pp. 217-228). New York, NY: Oxford University Press.

Damasio, H., & Frank, R. (1992). Three-dimensional in vivo mapping of brain lesions in humans. *Archives of Neurology, 49*, 137–143. doi: 10.1001/archneur.1992.00530260037016

Damasio, H., Grabowski, T., Frank, R., Galaburda, A. M., & Damasio, A. R. (1994). The return of Phineas Gage: The skull of a famous patient yields clues about the brain. *Science, 264*, 1102–1105. doi: 10.1126/science.8178168

Darwin, C. (1872, 1965). *The expression of the emotions in man and animals*. Chicago, IL: University of Chicago Press.

Davidson, R. J., Lewis, D. A., Alloy, L. B., Amaral, D. G., Bush, G., Cohen, J. D., . . . Peterson, B. S. (2002). Neural and behavioral substrates of mood and mood regulation. *Biological Psychiatry, 52*, 478–502. doi: 10.1016/S0006-3223(02)01458-0

Davis, M., & Whalen, P. J. (2001). The amygdala: Vigilance and emotion. *Molecular Psychology, 6*, 13–34.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Qué PASA? The posterior - anterior shift in aging. *Cerebral Cortex, 18*, 1201–1209. doi: 10.1093/cercor/bhm155

De Jong, R. (1995). The role of preparation in overlapping-task performance. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 48*, 2–25. doi: 10.1080/14640749508401372

De Kloet, E. R., Joels, M., & Holsboer, F. (2005). Stress and the brain: From adaptation to disease. *Nature Reviews. Neuroscience, 6*, 463–475. doi: 10.1038/nrn1683

De Martino, B., Kumaran, D., Seymour, B., & Dolan, R. J. (2006). Frames, biases, and rational decision-making in the human brain. *Science, 313*, 684–687. doi: 10.1126/science.1128356

De Vries, M., Holland, R. W., & Witteman, C. L. M. (2008a). Fitting decisions: Mood and intuitive versus deliberative decision strategies. *Cognition and Emotion, 22*, 931–943. doi: 10.1080/02699930701552580

De Vries, M., Holland, R. W., & Witteman, C. L. M. (2008b). In the winning mood: Affect in the Iowa Gambling Task. *Judgment and Decision Making, 3*, 42–50.

Deakin, J., Aitken, M., Robbins, T., & Sahakian, B. J. (2004). Risk taking during decision-making in normal volunteers changes with age. *Journal of the International Neuropsychological Society, 10*, 590–598. doi: 10.1017/S1355617704104104

Dedovic, K., D'Aguiar, C., & Pruessner, J. C. (2009). What stress does to your brain. *Canadien Journal of Psychiatry, 54*, 6–15.

Dedovic, K., Renwick, R., Mahani, N. K., Engert, V., Lupien, S., & Pruessner, J. C. (2005). The Montreal Imaging Stress Task: Using functional imaging to investigate the effects of perceiving and processing psychological stress in the human brain. *Journal of Psychiatry and Neuroscience, 30*, 319–325.

Dedovic, K., Rexroth, M., Wolff, E., Duchesne, A., Scherling, C., Beaudry, T., . . . Pruessner, J. C. (2009). Neural correlates of processing stressful information: An event-related fMRI study. *Brain Research, 1293*, 49–60. doi: 10.1016/j.brainres.2009.06.044

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology, 14*, 218–224. doi: 10.1016/j.conb.2004.03.008

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science, 284*, 970–974. doi: 10.1126/science.284.5416.970

Delazer, M., Högl, B., Zamarian, L., Wenter, J., Gschliesser, V., Ehrmann, L., . . . Frauscher, B. (2011). Executive functions, information sampling, and decision making in narcolepsy with cataplexy. *Neuropsychology, 25*, 477–487. doi: 10.1037/a0022357

Delazer, M., Sinz, H., Zamarian, L., & Benke, T. (2007). Decision-making with explicit and stable rules in mild Alzheimer's disease. *Neuropsychologia, 45*, 1632–1641. doi: 10.1016/j.neuropsychologia.2007.01.006

Delazer, M., Sinz, H., Zamarian, L., Stockner, H., Seppi, K., Wenning, G. K., . . . Poewe, W. (2009). Decision making under risk and under ambiguity in Parkinson's disease. *Neuropsychologia, 47*, 1901–1908. doi: 10.1016/j.neuropsychologia.2009.02.034

Denes-Raj, V., & Epstein, S. (1994). Conflict between intuitive and rational processing: When people behave against their better judgment. *Journal of Personality and Social Psychology, 66*, 819–829. doi: 10.1037/0022-3514.66.5.819

Depp, C., Vahia, I. V., & Jeste, D. (2010). Successful aging: Focus on cognitive and emotional health. *Annual Review of Clinical Psychology, 6*, 527–550. doi: 10.1146/annurev.clinpsy.121208.131449

Deprez, S., Vandenbulcke, M., Peeters, R., Emsell, L., Amant, F., & Sunaert, S. (2013). The functional neuroanatomy of multitasking: Combining dual tasking with a short term memory task. *Neuropsychologia, 51*, 2251–2260. doi: 10.1016/j.neuropsychologia.2013.07.024

Derefinko, K. J., Adams, Z. W., Milich, R., Fillmore, M. T., Lorch, E. P., & Lynam, D. R. (2008). Response style differences in the inattentive and combined subtypes of attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology, 36*, 745–758. doi: 10.1007/s10802-007-9207-3

Dickerson, S. S., & Kemeny, M. E. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin, 130*, 355–391. doi: 10.1037/0033-2909.130.3.355

Dijker, A. J., & Koomen, W. (1996). Stereotyping and attitudinal effects under time pressure. *European Journal of Social Psychology, 26*, 61–74.

Dillo, W., Göke, A., Prox-Vagedes, V., Szycik, G. R., Roy, M., Donnerstag, F., . . . Ohlmeier, M. D. (2010). Neuronal correlates of ADHD in adults with evidence for compensation strategies - A functional MRI study with a Go/No-Go paradigm. *German Medical Science, 8*, Doc09. doi: 10.3205/000098

Dolan, R. J. (2002). Emotion, cognition, and behavior. *Science, 298*, 1191–1194. doi: 10.1126/science.1076358

Dolcos, F., Diaz-Granados, P., Wang, L., & McCarthy, G. (2008). Opposing influences of emotional and non-emotional distracters upon sustained prefrontal cortex activity during a delayed-response working memory task. *Neuropsychologia, 46*, 326–335. doi: 10.1016/j.neuropsychologia.2007.07.010

Dolcos, F., Iordan, A. D., & Dolcos, S. (2011). Neural correlates of emotion–cognition interactions: A review of evidence from brain imaging investigations. *Journal of Cognitive Psychology, 23*, 669–694. doi: 10.1080/20445911.2011.594433

Dolcos, F., LaBar, K. S., & Cabeza, R. (2004). Interaction between the amygdala and the medial temporal lobe memory system predicts better memory for emotional events. *Neuron, 42*, 855–863. doi: 10.1016/S0896-6273(04)00289-2

Dolcos, F., LaBar, K. S., & Cabeza, R. (2005). Remembering one year later: Role of the amygdala and the medial temporal lobe memory system in retrieving emotional memories. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 2626–2631. doi: 10.1073/pnas.0409848102

Dolcos, F., & McCarthy, G. (2006). Brain systems mediating cognitive interference by emotional distraction. *Journal of Neuroscience, 26*, 2072–2079. doi: 10.1523/JNEUROSCI.5042-05.2006

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., & von Cramon, D. Y. (2000). Prefrontal cortex activation in task switching: An event-related fMRI study. *Brain Research. Cognitive Brain Research, 9*, 103–109. doi: 10.1016/S0926-6410(99)00029-4

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Changes in grey matter induced by training. *Nature, 427*, 311–312. doi: 10.1038/427311a

Drechsler, R. (2007). Exekutive Funktionen [Executive functions]. *Zeitschrift für Neuropsychologie, 18*, 233–248. doi: 10.1024/1016-264x.18.3.233

Drechsler, R., Rizzo, P., & Steinhausen, H.-C. (2007). Decision-making on an explicit risk-taking task in preadolescents with attention-deficit/hyperactivity disorder. *Journal of Neural Transmission, 115*, 201–209. doi: 10.1007/s00702-007-0814-5

Dreher, J.-C., & Grafman, J. (2003). Dissociating the roles of the rostral anterior cingulate and the lateral prefrontal cortices in performing two tasks simultaneously or successively. *Cerebral Cortex, 13*, 329–339. doi: 10.1093/cercor/13.4.329

Dubois, B., Slachevsky, A., Litvan, I., & Pillon, B. (2000). The FAB: A frontal assessment battery at bedside. *Neurology, 55*, 1621–1626. doi: 10.1212/wnl.55.11.1621

Dunn, B. D., Dalgleish, T., & Lawrence, A. D. (2006). The somatic marker hypothesis: A critical evaluation. *Neuroscience and Biobehavioral Reviews, 30*, 239–271. doi: 10.1016/j.neubiorev.2005.07.001

Durstewitz, D., & Seamans, J. K. (2008). The dual-state theory of prefrontal cortex dopamine function with relevance to catechol-o-methyltransferase genotypes and schizophrenia. *Biological Psychiatry, 64*, 739–749. doi: 10.1016/j.biopsych.2008.05.015

Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron, 52*, 1109–1120. doi: 10.1016/j.neuron.2006.11.009

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review, 66*, 183–201. doi: 10.1037/h0047707

Eatough, E. M., Shirtcliff, E. A., Hanson, J. L., & Pollak, S. D. (2009). Hormonal reactivity to MRI scanning in adolescents. *Psychoneuroendocrinology, 34*, 1242–1246. doi: 10.1016/j.psyneuen.2009.03.006

Ekman, P. (1978). *Manual for the facial action coding system*. Palo Alto, CA: Consulting Psychologist Press.

Ekman, P. (1982). *Emotion in the human face*. New York, NY: Cambridge University Press.

Ekman, P. (1993). Voluntary smiling changes regional brain activity. *Psychological Science, 4*, 342–345. doi: 10.1111/j.1467-9280.1993.tb00576.x

Elliott, R. (2003). Executive functions and their disorders: Imaging in clinical neuroscience. *British Medical Bulletin, 65*, 49–59. doi: 10.1093/bmb/65.1.49

Elster, A. D. (1994). *Questions and answeres in magnetic resonance imaging*. St. Louis, MO: Mosby.

Epstein, S. (1994). Integration of the cognitive and the psychodynamic unconscious. *American Psychologist, 49*, 709–724. doi: 10.1037/0003-066X.49.8.709

Epstein, S., Lipson, A., Holstein, C., & Huh, E. (1992). Irrational reactions to negative outcomes: Evidence for two conceptual systems. *Journal of Personality and Social Psychology, 62*, 328–339. doi: 10.1037/0022-3514.62.2.328

Epstein, S., & Pacini, R. (1999). Some basic issues regarding dual-process theories from the perspective of cognitive-experiential self-theory. In S. Chaiken & Y. Trope (Eds.), *Dual-process theories in social psychology* (pp. 462-482). New York, NY: Guilford Press.

Epstein, S., Pacini, R., Denes-Raj, V., & Heier, H. (1996). Individual differences in intuitive-experiential and analytical-rational thinking styles. *Journal of Personality and Social Psychology, 71*, 390–405. doi: 10.1037/0022-3514.71.2.390

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., & Kramer, A. F. (2005). Neural correlates of dual-task performance after minimizing task-preparation. *NeuroImage, 28*, 967–979. doi: 10.1016/j.neuroimage.2005.06.047

Erk, S., Kleczar, A., & Walter, H. (2007). Valence-specific regulation effects in a working memory task with emotional context. *NeuroImage, 37*, 623–632. doi: 10.1016/j.neuroimage.2007.05.006

Ernst, M., Bolla, K., Mouratidis, M., Matochik, J. A., Cadet, J.-L., London, E. D., . . . Contoreggi, C. (2002). Decision-making in a risk-taking task: A PET study. *Neuropsychopharmacology, 26*, 682–691. doi: 10.1016/S0893-133X%2801%2900414-6

Ernst, M., Nelson, E. E., McClure, E. B., Monk, C. S., Munson, S., Eshel, N., . . . Pine, D. S. (2004). Choice selection and reward anticipation: An fMRI study. *Neuropsychologia, 42*, 1585–1597. doi: 10.1016/j.neuropsychologia.2004.05.011

Eslinger, P. J., & Damasio, A. R. (1985). Severe disturbance of higher cognition after bilateral frontal lobe ablation: Patient EVR. *Neurology, 35*, 1731–1741. doi: 10.1212/WNL.35.12.1731

Eslinger, P. J., Lyon, G. R., & Krasnegor, N. A. (1996). Conceptualizing, describing and measuring components of attention: A summary. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 367-395). Baltimore, MD: Paul H. Brookes Publishing.

Euser, A. S., Meel, C. S., Snelleman, M., & Franken, I. H. A. (2011). Acute effects of alcohol on feedback processing and outcome evaluation during risky decision-making: An ERP study. *Psychopharmacology, 217*, 111–125. doi: 10.1007/s00213-011-2264-x

Euteneuer, F., Schaefer, F., Stuermer, R., Boucsein, W., Timmermann, L., Barbe, M. T., . . . Kalbe, E. (2009). Dissociation of decision-making under ambiguity and decision-making under risk in patients with Parkinson's disease: A neuropsychological and psychophysiological study. *Neuropsychologia, 47*, 2882–2890. doi: 10.1016/j.neuropsychologia.2009.06.014

Evans, J. S. B. T. (2003). In two minds: Dual-process accounts of reasoning. *Trends in Cognitive Sciences, 7*, 454–459. doi: 10.1016/j.tics.2003.08.012

Evans, J. S. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology, 59*, 255–278. doi: 10.1146/annurev.psych.59.103006.093629

Evans, J. S. B. T., & Stanovich, K. E. (2013). Dual-Process theories of higher cognition: Advancing the debate. *Perspectives on Psychological Science, 8*, 223–241. doi: 10.1177/1745691612460685

Ewert, O. (1983). Ergebnisse und Probleme der Emotionsforschung [Results and problems in research of emotions]. In H. Thomae (Ed.), *Enzyklopädie der Psychologie, Teilband IV/1, Theorien und Formen der Motivation [Encyclopedia of psychology, Vol. IV/1, Theories and types of motivation]* (pp. 397-452). Göttingen, Germany: Hogrefe.

Fassbender, C., Murphy, K., Foxe, J. J., Wylie, G. R., Javitt, D. C., Robertson, I. H., & Garavan, H. (2004). A topography of executive functions and their interactions revealed by functional magnetic resonance imaging. *Brain Research. Cognitive Brain Research, 20*, 132–143. doi: 10.1016/j.cogbrainres.2004.02.007

Fellows, L. K., & Farah, M. J. (2003). Ventromedial frontal cortex mediates affective shifting in humans: Evidence from a reversal learning paradigm. *Brain, 126*, 1830–1837. doi: 10.1093/brain/awg180

Fellows, L. K., & Farah, M. J. (2005). Different underlying impairments in decision-making following ventromedial and dorsolateral frontal lobe damage in humans. *Cerebral Cortex, 15*, 58–63. doi: 10.1093/cercor/bhh108

Ferguson, S. M., Eskenazi, D., Ishikawa, M., Wanat, M. J., Phillips, P. E. M., Dong, Y., . . . Neumaier, J. F. (2011). Transient neuronal inhibition reveals opposing roles of indirect and direct pathways in sensitization. *Nature Neuroscience, 14*, 22–24. doi: 10.1038/nn.2703

Ferrier, D. (1878). The Goulstonian Lectures on the localisation of cerebral disease. *British Medical Journal, 1*, 443–447.

Finucane, M. L., Alhakami, A., Slovic, P., & Johnson, S. M. (2000). The affect heuristic in judgments of risks and benefits. *Journal of Behavioral Decision Making, 13*, 1–17.

Fishbein, D., Hyde, C., Eldreth, D., London, E. D., Matochik, J., Ernst, M., . . . Kimes, A. (2005). Cognitive performance and autonomic reactivity in abstinent drug abusers and nonusers. *Experimental and Clinical Psychopharmacology, 13*, 25–40. doi: 10.1037/1064-1297.13.1.25

Flowers, K. A., & Robertson, C. (1985). The effect of Parkinson's disease on the ability to maintain a mental set. *Journal of Neurology, Neurosurgery and Psychiatry, 48*, 517–529. doi: 10.1136/jnnp.48.6.517

Fond, G., Bayard, S., Capdevielle, D., Del-Monte, J., Mimoun, N., Macgregor, A., . . . Raffard, S. (2012). A further evaluation of decision-making under risk and under ambiguity in schizophrenia. *European Archives of Psychiatry and Clinical Neuroscience, 263*, 249–257. doi: 10.1007/s00406-012-0330-y

Forstmann, B. U., Brass, M., Koch, I., & von Cramon, D. Y. (2006). Voluntary selection of task sets revealed by functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 18*, 388–398. doi: 10.1162/089892906775990589

Forstmann, B. U., Ridderinkhof, K. R., Kaiser, J., & Bledowski, C. (2007). At your own peril: An ERP study of voluntary task set selection processes in the medial frontal cortex. *Cognitive, Affective, & Behavioral Neuroscience, 7*, 286–296. doi: 10.3758/cabn.7.4.286

Fox, E. (2008). *Emotion science: An integration of cognitive and neuroscientific approache*. Basingstoke, UK: Palgrave Macmillan.

Fox, P. T., & Raichle, M. E. (1986). Focal physiological uncoupling of cerebral blood flow and oxidative metabolism during somatosensory stimulation in human subjects. *Proceedings of the National Academy of Sciences of the United States of America, 83*, 1140–1144. doi: 10.2307/27111

Friston, K. J. (2002). Beyond phrenology: What can neuroimaging tell us about distributed circuitry? *Annual Review of Neuroscience, 25*, 221–250. doi: 10.1146/annurev.neuro.25.112701.142846

Frith, C. D., Friston, K. J., Liddle, P. F., & Frackowiak, R. S. J. (1991). Willed action and the prefrontal cortex in man: A study with PET. *Proceedings of the Royal Society of London. Series B, Biological Sciences, 244*, 241–246. doi: 10.1098/rspb.1991.0077

Fukui, H., Murai, T., Fukuyama, H., Hayashi, T., & Hanakawa, T. (2005). Functional activity related to risk anticipation during performance of the Iowa Gambling Task. *NeuroImage, 24*, 253–259. doi: 10.1016/j.neuroimage.2004.08.028

Fukunaga, R., Brown, J. W., & Bogg, T. (2012). Decision making in the Balloon Analogue Risk Task (BART): Anterior cingulate cortex signals loss aversion but not the infrequency of risky choices. *Cognitive, Affective, & Behavioral Neuroscience, 12*, 479–490. doi: 10.3758/s13415-012-0102-1

Gathercole, S. E. (1994). Neuropsychology and working memory: A review. *Neuropsychology, 8*, 494–505. doi: 10.1037/0894-4105.8.4.494

Gathmann, B., Pawlikowski, M., Schöler, T., & Brand, M. (2014). Performing a secondary executive task with affective stimuli interferes with decision making under risk conditions. *Cognitive Processing, 15*, 113–126. doi: 10.1007/s10339-013-0584-y

Gathmann, B., Schulte, F. P., Maderwald, S., Pawlikowski, M., Starcke, K., Schäfer, L. C., . . . Brand, M. (2014). Stress and decision making: Neural correlates of the interaction between stress, executive functions, and decision making under risk. *Experimental Brain Research, 232*, 957–973. doi: 10.1007/s00221-013-3808-6

Gazes, Y., Rakitin, B. C., Steffener, J., Habeck, C., Butterfield, B., Ghez, C., & Stern, Y. (2010). Performance degradation and altered cerebral activation during dual performance: Evidence for a bottom-up attentional system. *Behavioural Brain Research, 210*, 229–239. doi: 10.1016/j.bbr.2010.02.036

Gläscher, J., Adolphs, R., Damasio, H., Bechara, A., Rudrauf, D., Calamia, M., . . . Tranel, D. (2012). Lesion mapping of cognitive control and value-based decision making in the prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America, 109*, 14681–14686. doi: 10.1073/pnas.1206608109

Gleichgerrcht, E., Ibanez, A., Roca, M., Torralva, T., & Manes, F. (2010). Decision-making cognition in neurodegenerative diseases. *Nature Reviews. Neurology, 6*, 611–623. doi: 10.1038/nrneurol.2010.148

Godefroy, O., Cabaret, M., Petit-Chenal, V., Pruvo, J.-P., & Rousseaux, M. (1999). Control Functions of the Frontal Lobes. Modularity of the Central-Supervisory System? *Cortex, 35*, 1–20. doi: 10.1016/S0010-9452(08)70782-2

Goebel, R. (2007). Localization of brain activity using functional magnetic resonance imaging. In C. Stippich (Ed.), Clinical functional MRI: Presurgical functional neuroimaging. In A. L. Baert, M. Knauth & K. Sartor (Series Eds.), Medical Radiology, Diagnostic Imaging (pp. 9-52). Berlin [etc], Germany: Springer. doi: 10.1007/978-3-540-49976-3

Goebel, R., & Kriegeskorte, N. (2005a). Funktionelle Magnetresonanztomopraphie [Functional magnetic resonance imaging]. In H. Walter (Ed.), *Funktionelle Bildgebung in Psychiatrie und Psychotherapie. Methodische Grundlagen und klinische Anwendungen [Functional imaging in psychiatry and psychotherapy. Methodical principles and clinical application]* (pp. 31-58). Stuttgart, Germany: Schattauer.

Goebel, R., & Kriegeskorte, N. (2005b). Funktionelle Magnetresonanztomopraphie [Functional magnetic resonance imaging]. In H. Walter (Ed.), *Funktionelle Bildgebung in Psychiatrie und Psychotherapie. Methodische Grundlagen und klinische Anwendungen [Functional imaging in psychiatry and psychotherapy. Methodical principles and clinical application]* (pp. 22-30). Stuttgart, Germany: Schattauer.

Goel, V., & Dolan, R. J. (2003). Explaining modulation of reasoning by belief. *Cognition, 87*, B11–B22. doi: 10.1016/S0010-0277(02)00185-3

Goldstein, R. Z., & Volkow, N. D. (2002). Drug addiction and its underlying neurobiological basis: Neuroimaging evidence for the involvement of the frontal cortex. *American Journal of Psychiatry, 159*, 1642–1652. doi: 10.1176/appi.ajp.159.10.1642

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology. General, 129*, 308–339. doi: 10.1037/0096-3445.129.3.308

Goto, Y., & Grace, A. A. (2005). Dopaminergic modulation of limbic and cortical drive of nucleus accumbens in goal-directed behavior. *Nature Neuroscience, 8*, 805–812. doi: 10.1038/nn1471

Goutte, C., Nielsen, F. A., & Hansen, L. K. (2000). Modeling the hemodynamic response in fMRI using smooth FIR filters. *IEEE Transactions on Medical Imaging, 19*, 1188–1201. doi: 10.1109/42.897811

Grady, C. L. (2008). Cognitive neuroscience of aging. *Annals of the New York Academy of Sciences, 1124*, 127–144. doi: 10.1196/annals.1440.009

Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A., . . . Haxby, J. V. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *Journal of Neuroscience, 14*, 1450–1462.

Grant, J. E., Chamberlain, S. R., Schreiber, L., & Odlaug, B. L. (2012). Neuropsychological deficits associated with cannabis use in young adults. *Drug and Alcohol Dependence, 121*, 159–162. doi: 10.1016/j.drugalcdep.2011.08.015

Gray, J. R., Braver, T. S., & Raichle, M. E. (2002). Integration of emotion and cognition in the lateral prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 4115–4120. doi: 10.1073/pnas.062381899

Greene, J. D., Hodges, J. R., & Baddeley, A. D. (1995). Autobiographical memory and executive function in early dementia of Alzheimer type. *Neuropsychologia, 33*, 1647–1670. doi: 10.1016/0028-3932(95)00046-1

Grimm, S., Weigand, A., Kazzer, P., Jacobs, A. M., & Bajbouj, M. (2012). Neural mechanisms underlying the integration of emotion and working memory. *NeuroImage, 61*, 1188–1194. doi: 10.1016/j.neuroimage.2012.04.004

Grisham, J. R., Norberg, M. M., Williams, A. D., Certoma, S. P., & Kadib, R. (2010). Categorization and cognitive deficits in compulsive hoarding. *Behaviour Research and Therapy, 48*, 866–872. doi: 10.1016/j.brat.2010.05.011

Gross, J. J. (1998). Antecedent- and response-focused emotion regulation: Divergent consequences for experience, expression, and physiology. *Journal of Personality and Social Psychology, 74*, 224–237. doi: 10.1037/0022-3514.74.1.224

Gross, J. J. (2002). Emotion regulation: Affective, cognitive, and social consequences. *Psychophysiology, 39*, 281–291. doi: 10.1017/s0048577201393198

Grossman, M., Cooke, A., DeVita, C., Alsop, D., Detre, J., Chen, W., & Gee, J. (2002). Age-related changes in working memory during sentence comprehension: An fMRI study. *NeuroImage, 15*, 302–317. doi: 10.1006/nimg.2001.0971

Hall, H., Sedvall, G., Magnusson, O., Kopp, J., Halldin, C., & Farde, L. (1994). Distribution of D1- and D2-dopamine receptors, and dopamine and its metabolites in the human brain. *Neuropsychopharmacology, 11*, 245–256.

Harlow, J. M. (1848). Passage of an iron rod through the head. *Boston Medical and Surgical Journal, 39*, 389–393.

Harlow, J. M. (1868). Recovery from the passage of an iron bar through the head. *Publications of the Massachusetts Medical Society, 2*, 327–347.

Harrison, B. J., Olver, J. S., Norman, T. R., Burrows, G. D., Wesnes, K. A., & Nathan, P. J. (2004). Selective effects of acute serotonin and catecholamine depletion on memory in healthy women. *Journal of Psychopharmacology, 18*, 32–40. doi: 10.1177/0269881104040225

Härting, C., Markowitsch, H. J., Neufeld, H., Calabrese, P., Deisinger, K., & Kessler, J. (2000). *Wechsler Gedächtnistest - Revidierte Fassung [Wechsler Memory Scale - revised version]*. Bern, Switzerland: Hans Huber Verlag.

Hartley, A. A., & Little, D. M. (1999). Age-related differences and similarities in dual-task interference. *Journal of Experimental Psychology. General, 128*, 416–449. doi: 10.1037/0096-3445.128.4.416

Harvey, P. D., Reichenberg, A., Romero, M., Granholm, E., & Siever, L. J. (2006). Dual-task information processing in schizotypal personality disorder: Evidence of impaired processing capacity. *Neuropsychology, 20*, 453–460. doi: 10.1037/0894-4105.20.4.453

Hautzel, H., Mottaghy, F. M., Specht, K., Müller, H.-W., & Krause, B. J. (2009). Evidence of a modality-dependent role of the cerebellum in working memory? An fMRI study comparing verbal and abstract n-back tasks. *NeuroImage, 47*, 2073–2082. doi: 10.1016/j.neuroimage.2009.06.005

Heilman, R. M., Crişan, L. G., Houser, D., Miclea, M., & Miu, A. C. (2010). Emotion regulation and decision making under risk and uncertainty. *Emotion, 10*, 257–265. doi: 10.1037/a0018489

Helmstaedter, C., Lendt, M., & Lux, S. (2001). *Verbaler Lern- und Merkfähigkeitstest [Verbal learning and memory test]*. Göttingen, Germany: Beltz Test.

Henckens, M. J. A. G., Van Wingen, G. A., Joëls, M., & Fernández, G. (2011). Time-dependent corticosteroid modulation of prefrontal working memory processing. *Proceedings of the National Academy of Sciences of the United States of America, 108*, 5801–5806. doi: 10.1073/pnas.1019128108

Henke, K., Weber, B., Kneifel, S., Wieser, H. G., & Buck, A. (1999). Human hippocampus associates information in memory. *Proceedings of the National Academy of Sciences of the United States of America, 96*, 5884–5889. doi: 10.1073/pnas.96.10.5884

Herman, J. P., Ostrander, M. M., Mueller, N. K., & Figueiredo, H. (2005). Limbic system mechanisms of stress regulation: Hypothalamo-pituitary-adrenocortical axis. *Progress in Neuro-Psychopharmacology & Biological Psychiatry, 29*, 1201–1213. doi: 10.1016/j.pnpbp.2005.08.006

Het, S., Rohleder, N., Schoofs, D., Kirschbaum, C., & Wolf, O. T. (2009). Neuroendocrine and psychometric evaluation of a placebo version of the 'Trier Social Stress Test'. *Psychoneuroendocrinology, 34*, 1075–1086. doi: 10.1016/j.psyneuen.2009.02.008

Heyder, K., Suchan, B., & Daum, I. (2004). Cortico-subcortical contributions to executive control. *Acta Psychologica, 115*, 271–289. doi: 10.1016/j.actpsy.2003.12.010

Hikida, T., Kimura, K., Wada, N., Funabiki, K., & Nakanishi, S. (2010). Distinct roles of synaptic transmission in direct and indirect striatal pathways to reward and aversive behavior. *Neuron, 66*, 896–907. doi: 10.1016/j.neuron.2010.05.011

Hines, E. A., & Brown, E. G. (1932). A standard stimulus for measuring vasomotor reactions: Its application in the study of hypertension. *Proceedings of the Staff Meeting in the Mayo Clinic, 7*, 332.

Hinson, J. M., Jameson, T. L., & Whitney, P. (2002). Somatic markers, working memory, and decision making. *Cognitive, Affective, & Behavioral Neuroscience, 2*, 341–353. doi: 10.3758/CABN.2.4.341

Hobson, P., & Leeds, L. (2001). Executive functioning in older people. *Reviews in Clinical Gerontology, 11*, 361–372. doi: 10.1017/S0959259801011479

Holland, P. C., & Gallagher, M. (1999). Amygdala circuitry in attentional and representational processes. *Trends in Cognitive Sciences, 3*, 65–73. doi: 10.1016/S1364-6613(98)01271-6

Horn, W. (1983). *Leistungsprüfsystem [German intelligence test battery]*. Göttingen, Germany Hogrefe.

Hoult, D. I. (2000). The principle of reciprocity in signal strength calculations - A mathematical guide. *Concepts in Magnetic Resonance, 12*, 173–179. doi: 10.1002/1099-0534(2000)12:4<173::AID-CMR1>3.0.CO;2-Q

Hsu, M., Bhatt, M., Adolphs, R., Tranel, D., & Camerer, C. F. (2005). Neural systems responding to degrees of uncertainty in human decision-making. *Science, 310*, 1680–1683. doi: 10.1126/science.1115327

Hu, L., & Bentler, P. M. (1995). Evaluating model fit. In R. H. Hoyle (Ed.), *Structural equation modeling. Concepts, issues, and application* (pp. 76-99). London, UK: Sage.

Hu, L., & Bentler, P. M. (1998). Fit indices in covariance structure modeling: Sensitivity to underparameterized model misspecification. *Psychological Methods, 3*, 424–453. doi: 10.1037/1082-989X.3.4.424

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*, 1–55. doi: 10.1080/10705519909540118

Huettel, S. A., Song, A. W., & McCarthy, G. (2009). *Functional magnetic resonance imaging* (2 ed.). Sunderland, MA: Sinauer Associates, Inc.

Hutson, P. H., Patel, S., Jay, M. T., & Barton, C. L. (2004). Stress-induced increase of cortical dopamine metabolism: Attenuation by a tachykinin NK1 receptor antagonist. *European Journal of Pharmacology, 484*, 57–64. doi: 10.1016/j.ejphar.2003.10.057

Hyafil, A., Summerfield, C., & Koechlin, E. (2009). Two mechansisms for task switching in the prefrontal cortex. *Journal of Neuroscience, 29*, 5135–5142. doi: 10.1523/JNEUROSCI.2828-08.2009

Ishai, A., Pessoa, L., Bikle, P. C., & Ungerleider, L. G. (2004). Repetition suppression of faces is modulated by emotion. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 9827–9832. doi: 10.1073/pnas.0403559101

Ito, H., Kanno, I., Hatazawa, J., & Miura, S. (2003). Changes in human cerebral blood flow and myocardial blood flow during mental stress measured by dual positron emission tomography. *Annals of Nuclear Medicine, 17*, 381–386. doi: 10.1007/bf03006605

Jaeggi, S. M., Seewer, R., Nirkko, A. C., Eckstein, D., Schroth, G., Groner, R., & Gutbrod, K. (2003). Does excessive memory load attenuate activation in the prefrontal cortex? Load-dependent processing in single and dual tasks: Functional magnetic resonance imaging study. *NeuroImage, 19*, 210–225. doi: 10.1016/S1053-8119(03)00098-3

Jahanshahi, M., Dirnberger, G., Fuller, R., & Frith, C. D. (2000). The role of the dorsolateral prefrontal cortex in random number generation: A study with positron emission tomography. *NeuroImage, 12*, 713–725. doi: 10.1006/nimg.2000.0647

James, W. (1890, 1950). *Principles of Psychology* (Vol. 1 & 2). New York, NY: Dover.

Jameson, T. L., Hinson, J. M., & Whitney, P. (2004). Components of working memory and somatic markers in decision making. *Psychonomic Bulletin and Review, 11*, 515–520. doi: 10.3758/BF03196604

Jersild, A. T. (1927). Mental set and mental shift. *Archives of Psychology, 89*.

Jones, S., Nyberg, L., Sandblom, J., Stigsdotter Neely, A., Ingvar, M., Magnus Petersson, K., & Bäckman, L. (2006). Cognitive and neural plasticity in aging: General and task-specific limitations. *Neuroscience and Biobehavioral Reviews, 30*, 864–871. doi: 10.1016/j.neubiorev.2006.06.012

Jurado, M., & Rosselli, M. (2007). The elusive nature of executive functions: A review of our current understanding. *Neuropsychology Review, 17*, 213–233. doi: 10.1007/s11065-007-9040-z

Just, M. A., Carpenter, P. A., Keller, T. A., Emery, L., Zajac, H., & Thulborn, K. R. (2001). Interdependence of nonoverlapping cortical systems in dual cognitive tasks. *NeuroImage, 14*, 417–426. doi: 10.1006/nimg.2001.0826

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kahneman, D. (2003). A perspective on judgment and choice: Mapping bounded rationality. *American Psychologist, 58*, 697–720. doi: 10.1037/0003-066X.58.9.697

Kahneman, D., & Frederick, S. (2002). Representativeness revisited: Attribute substitution in intuitive judgment. In T. Gilovich, D. Griffin & D. Kahneman (Eds.), *Heuristics and biases* (pp. 49-81). New York, NY: Cambridge University Press.

Kahneman, D., & Frederick, S. (2007). Frames and brains: Elicitation and control of response tendencies. *Trends in Cognitive Sciences, 11*, 45–46. doi: 10.1016/j.tics.2006.11.007

Kalbe, E., Kessler, J., Calabrese, P., Smith, R., Passmore, A. P., Brand, M., & Bullock, R. (2004). DemTect: A new, sensitive cognitive screening test to support the diagnosis of mild cognitive impairment and early dementia. *International Journal of Geriatric Psychiatry, 19*, 136–143. doi: 10.1002/gps.1042

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science, 12*, 978–990. doi: 10.1111/j.1467-7687.2009.00846.x

Kaufmann, L., Koppelstaetter, F., Delazer, M., Siedentopf, C., Rhomberg, P., Golaszewski, S., . . . Ischebeck, A. (2005). Neural correlates of distance and congruity effects in a numerical Stroop task: An event-related fMRI study. *NeuroImage, 25*, 888–898. doi: 10.1016/j.neuroimage.2004.12.041

Keele, S. W. (1973). *Attention and human performance*. Pacific Palisades, CA: Goodyear.

Keeser, D., Padberg, F., Reisinger, E., Pogarell, O., Kirsch, V., Palm, U., . . . Mulert, C. (2011). Prefrontal direct current stimulation modulates resting EEG and event-related potentials in healthy subjects: A standardized low resolution tomography (sLORETA) study. *NeuroImage, 55*, 644–657. doi: 10.1016/j.neuroimage.2010.12.004

Kelly, A. M. C., & Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cerebral Cortex, 15*, 1089–1102. doi: 10.1093/cercor/bhi005

Kensinger, E. A., & Corkin, S. (2003). Effect of negative emotional content on working memory and long-term memory. *Emotion, 3*, 378–393. doi: 10.1037/1528-3542.3.4.378

Khan, Z. U., Gutiérrez, A., Martín, R., Peñafiel, A., Rivera, A., & De La Calle, A. (1998). Differential regional and cellular distribution of dopamine D2-like receptors: An immunocytochemical study of subtype-specific antibodies in rat and human brain. *Journal of Comparative Neurology, 402*, 353–371. doi: 10.1002/(sici)1096-9861(19981221)402:3<353::aid-cne5>3.0.co;2-4

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - A review. *Psychological Bulletin, 136*, 849–874. doi: 10.1037/a0019842

Kim, M. A., Tura, E., Potkin, S. G., Fallon, J. H., Manoach, D. S., Calhoun, V. D., & Turner, J. A. (2010). Working memory circuitry in schizophrenia shows widespread cortical inefficiency and compensation. *Schizophrenia Research, 117*, 42–51. doi: 10.1016/j.schres.2009.12.014

Kim, Y.-T., Sohn, H., & Jeong, J. (2011). Delayed transition from ambiguous to risky decision making in alcohol dependence during Iowa Gambling Task. *Psychiatry Research, 190*, 297–303. doi: 10.1016/j.psychres.2011.05.003

Kirschbaum, C., & Hellhammer, D. H. (1994). Salivary cortisol in psychoneuroendocrine research: Recent developments and applications. *Psychoneuroendocrinology, 19*, 313–333. doi: 10.1016/0306-4530(94)90013-2

Kirschbaum, C., Pirke, K.-m., & Hellhammer, D. H. (1995). Preliminary evidence for reduced cortisol responsivity to psychological stress in women using oral contraceptive medication. *Psychoneuroendocrinology, 20*, 509–514. doi: 10.1016/0306-4530(94)00078-O

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test' - A tool for investigating psychobiological stress responses in laboratory setting. *Neurospsychobiology, 28*, 77–81. doi: 10.1159/000119004

Kirschbaum, C., Wüst, S., & Hellhammer, D. (1992). Consistent sex differences in cortisol responses to psychological stress. *Psychosomatic Medicine, 54*, 648-657.

Kleeberg, J., Bruggimann, L., Annoni, J.-M., van Melle, G., Bogousslavsky, J., & Schluep, M. (2004). Altered decision-making in multiple sclerosis: A sign of impaired emotional reactivity? *Annals of Neurology, 56*, 787–795. doi: 10.1002/ana.20277

Kleindorfer, P. R., Kunreuther, H., & Schoemaker, P. J. H. (1993). *Decision sciences: An integrative perspective*. Cambridge, UK: Cambridge University Press.

Klingberg, T. (1998). Concurrent performance of two working memory tasks: Potential mechanisms of interference. *Cerebral Cortex, 8*, 593–601. doi: 10.1093/cercor/8.7.593

Klingberg, T. (2000). Limitations in information processing in the human brain: Neuroimaging of dual task performance and working memory tasks. In H. B. M. Uylings, C. G. Van Eden, J. P. C. De Bruin, M. G. P. Feenstra & C. M. A. Pennartz (Eds.), *Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures* (Vol. 126, pp. 95-102). Amsterdam, Netherlands: Elsevier Science.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences, 14*, 317–324. doi: 10.1016/j.tics.2010.05.002

Knops, A., Nuerk, H.-C., Fimm, B., Vohn, R., & Willmes, K. (2006). A special role for numbers in working memory? An fMRI study. *NeuroImage, 29*, 1–14. doi: 10.1016/j.neuroimage.2005.07.009

Koch, I., Gade, M., Schuch, S., & Philipp, A. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin and Review, 17*, 1–14. doi: 10.3758/pbr.17.1.1

Koechlin, E., Basso, G., Pietrini, P., Panzer, S., & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature, 399*, 148–151. doi: 10.1038/20178

Koechlin, E., & Hyafil, A. (2007). Anterior prefrontal function and the limits of human decision-making. *Science, 318*, 594–598. doi: 10.2307/20051445

Kohno, M., Ghahremani, D. G., Morales, A. M., Robertson, C. L., Ishibashi, K., Morgan, A. T., . . . London, E. D. (in press). Risk-taking behavior: Dopamine D2/D3 receptors, feedback, and frontolimbic activity. *Cerebral Cortex*. doi: 10.1093/cercor/bht218

Koolhaas, J. M., Bartolomucci, A., Buwalda, B., de Boer, S. F., Flugge, G., Korte, S. M., . . . Fuchs, E. (2011). Stress revisited: A critical evaluation of the stress concept. *Neuroscience and Biobehavioral Reviews, 35*, 1291–1301. doi: 10.1016/j.neubiorev.2011.02.003

Koric, L., Volle, E., Seassau, M., Bernard, F. A., Mancini, J., Dubois, B., . . . Levy, R. (2012). How cognitive performance-induced stress can influence right VLPFC activation: An fMRI study in healthy subjects and in patients with social phobia. *Human Brain Mapping, 33*, 1973–1986. doi: 10.1002/hbm.21340

Kravitz, A. V., Tye, L. D., & Kreitzer, A. C. (2012). Distinct roles for direct and indirect pathway striatal neurons in reinforcement. *Nature Neuroscience, 15*, 816–818. doi: 10.1038/nn.3100

Kray, J., Karbach, J., Haenig, S., & Freitag, C. (2012). Can task-switching training enhance executive control functioning in children with attention deficit/-hyperactivity disorder? *Frontiers in Human Neuroscience, 5:180*. doi: 10.3389/fnhum.2011.00180

Kudielka, B. M., Hellhammer, D. H., & Wust, S. (2009). Why do we respond so differently? Reviewing determinants of human salivary cortisol responses to challenge. *Psychoneuroendocrinology, 34*, 2–18. doi: 10.1016/j.psyneuen.2008.10.004

Kukolja, J., Thiel, C. M., Wolf, O. T., & Fink, G. R. (2008). Increased cortisol levels in cognitively challenging situations are beneficial in young but not older subjects. *Psychopharmacology, 201*, 293–304. doi: 10.1007/s00213-008-1275-8

Kumsta, R., Entringer, S., Koper, J. W., van Rossum, E. F. C., Hellhammer, D. H., & Wüst, S. (2007). Sex specific associations between common glucocorticoid receptor gene variants and hypothalamus-pituitary-adrenal axis responses to psychosocial stress. *Biological Psychiatry, 62*, 863–869. doi: 10.1016/j.biopsych.2007.04.013

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, I. E., Weisskoff, R. M., Poncelet, B. E., . . . Rosen, B. R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceedings of the National Academy of Sciences of the United States of America, 89*, 5675-5679. doi: 10.1073/pnas.89.12.5675

LaBar, K. S., Gatenby, J. C., Gore, J. C., LeDoux, J. E., & Phelps, E. A. (1998). Human amygdala activation during conditioned fear acquisition and extinction: A mixed-trial fMRI study. *Neuron, 20*, 937–945. doi: 10.1016/S0896-6273(00)80475-4

Labudda, K., Brand, M., Mertens, M., Ollech, I., Markowitsch, H. J., & Woermann, F. G. (2010). Decision making under risk condition in patients with Parkinson's disease: A behavioural and fMRI study. *Behavioural Neurology, 23*, 131–143. doi: 10.3233/ben-2010-0277

Labudda, K., Frigge, K., Horstmann, S., Aengenendt, J., Woermann, F. G., Ebner, A., . . . Brand, M. (2009). Decision making in patients with temporal lobe epilepsy. *Neuropsychologia, 47*, 50–58. doi: dx.doi.org/10.1016/j.neuropsychologia.2008.08.014

Labudda, K., Woermann, F. G., Mertens, M., Pohlmann-Eden, B., Markowitsch, H. J., & Brand, M. (2008). Neural correlates of decision making with explicit information about probabilities and incentives in elderly healthy subjects. *Experimental Brain Research, 187*, 641–650. doi: 10.1007/s00221-008-1332-x

Labudda, K., Wolf, O. T., Markowitsch, H. J., & Brand, M. (2007). Decision-making and neuroendocrine responses in pathological gamblers. *Psychiatry Research, 153*, 233–243. doi: 10.1016/j.psychres.2007.02.002

Laier, C., Pawlikowski, M., & Brand, M. (2013). Sexual picture processing interferes with decision-making under ambiguity. *Archives of Sexual Behavior*, 1–10. doi: 10.1007/s10508-013-0119-8

Laier, C., Schulte, F. P., & Brand, M. (2012). Pornographic picture processing interferes with working memory performance. *Journal of Sex Research*, 1–11. doi: 10.1080/00224499.2012.716873

Lancaster, J. L., Summerln, J. L., Rainey, L., Freitas, C. S., & Fox, P. T. (1997). The Talairach daemon, a database server for Talairach atlas labels. *NeuroImage, 5*, S633.

Lancaster, J. L., Woldorff, M. G., Parsons, L. M., Liotti, M., Freitas, C. S., Rainey, L., . . . Fox, P. T. (2000). Automated Talairach atlas labels for functional brain mapping. *Human Brain Mapping, 10*, 120–131. doi: 10.1002/1097-0193(200007)10:3<120::aid-hbm30>3.0.co;2-8

Lane, R. D., Reiman, E. M., Axelrod, B., Yun, L.-S., Holmes, A., & Schwartz, G. E. (1998). Neural correlates of levels of emotional awareness: Evidence of an interaction between emotion and attention in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 10*, 525–535. doi: 10.1162/089892998562924

Lang, P. J. (1980). Behavioral treatment and bio-behavioral assessment: Computer applications. In J. B. Sidowski, J. H. Johnson & T. A. Williams (Eds.), *Technology in mental health care delivery systems* (pp. 119-137). Norwood, NJ: Ablex.

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). *International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical Report A-8*. Universitiy of Florida, Gainsville, FL.

Lawrence, N. S., Jollant, F., O'Daly, O., Zelaya, F., & Phillips, M. L. (2009). Distinct roles of prefrontal cortical subregions in the Iowa Gambling Task. *Cerebral Cortex, 19*, 1134–1143. doi: 10.1093/cercor/bhn154

Lazarus, R. S. (1966). *Psychological stress and the coping process*. New York, NY: McGraw-Hill.

Lazarus, R. S. (1991a). Cognition and motivation in emotion. *American Psychologist, 46*, 352–367. doi: 10.1037/0003-066x.46.4.352

Lazarus, R. S. (1991b). *Emotion and adaption*. New York, NY: Oxford University Press.

Lazarus, R. S. (1993). From psychological stress to emotions: A history of changing outlooks. *Annual Review of Psychology, 44*, 1–21. doi: 10.1146/annurev.ps.44.020193.000245

Lazarus, R. S. (1999). *Stress and emotion: A new synthesis*. New York, NY: Springer Publishing Company Inc.

Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal and coping*. New York, NY: Springer Publishing Company Inc.

Lazarus, R. S., & Launier, R. (1978). Stress-related transactions between person and environment. In L. A. Pervin & M. Lewis (Eds.), *Perspectives in interactional psychology* (pp. 387-327). New York, NY: Plenum.

Lazarus, R. S., & Smith, C. A. (1988). Knowledge and appraisal in the cognition-emotion relationship. *Cognition and Emotion, 2*, 281–300. doi: 10.1080/02699938808412701

Lazeron, R. H. C., Rombouts, S. A. R. B., Machielsen, W. C. M., Scheltens, P., Witter, M. P., Uylings, H. B. M., & Barkhof, F. (2000). Visualizing brain activation during planning: The Tower of London test adapted for functional MR imaging. *American Journal of Neuroradiology, 21*, 1407–1414.

LeDoux, J. E. (1989). Cognitive-emotional interactions in the brain. *Cognition and Emotion, 3*, 267–289. doi: 10.1080/02699938908412709

Lehle, C., Steinhauser, M., & Hübner, R. (2009). Serial or parallel processing in dual tasks: What is more effortful? *Psychophysiology, 46*, 502–509. doi: 10.1111/j.1469-8986.2009.00806.x

Lehto, J. (1996). Are executive function tests dependent on working memory capacity? *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 49*, 29–50. doi: 10.1080/027249896392793

Lejuez, C. W., Read, J. P., Kahler, C. W., Richards, J. B., Ramsey, S. E., Stuart, G. L., . . . Brown, R. A. (2002). Evaluation of a behavioral measure of risk taking: The Balloon Analogue Risk Task (BART). *Journal of Experimental Psychology. Applied, 8*, 75–84. doi: 10.1037/1076-898x.8.2.75

Lerner, J. S., & Keltner, D. (2000). Beyond valence: Toward a model of emotion-specific influences on judgement and choice. *Cognition and Emotion, 14*, 473–493. doi: 10.1080/026999300402763

Lerner, J. S., & Keltner, D. (2001). Fear, anger, and risk. *Journal of Personality and Social Psychology, 81*, 146–159. doi: 10.1037/0022-3514.81.1.146

Levens, S. M., & Gotlib, I. H. (2010). Updating positive and negative stimuli in working memory in depression. *Journal of Experimental Psychology. General, 139*, 654–664. doi: 10.1037/a0020283

Lezak, M. D., Howieson, D. B., & Loring, D. W. (2004). *Neuropsychological assessment* (4 ed.). New York, NY: Oxford University Press.

Li, X., Lu, Z.-L., D'Argembeau, A., Ng, M., & Bechara, A. (2010). The Iowa Gambling Task in fMRI images. *Human Brain Mapping, 31*, 410–423. doi: 10.1002/hbm.20875

Lie, C.-H., Specht, K., Marshall, J. C., & Fink, G. R. (2006). Using fMRI to decompose the neural processes underlying the Wisconsin Card Sorting Test. *NeuroImage, 30*, 1038–1049. doi: 10.1016/j.neuroimage.2005.10.031

Liefooghe, B., Demanet, J., & Vandierendonck, A. (2010). Persisting activation in voluntary task switching: It all depends on the instructions. *Psychonomic Bulletin and Review, 17*, 381–386. doi: 10.3758/PBR.17.3.381

Liepelt, R., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Quarterly Journal of Experimental Psychology, 64*, 1251–1272. doi: 10.1080/17470218.2010.543284

Lighthall, N. R., Mather, M., & Gorlick, M. A. (2009). Acute stress increases sex differences in risk seeking in the Balloon Analogue Risk Task. *PLoS ONE, 4*, e6002. doi: 10.1371/journal.pone.0006002

Lighthall, N. R., Sakaki, M., Vasunilashorn, S., Nga, L., Somayajula, S., Chen, E. Y., . . . Mather, M. (2012). Gender differences in reward-related decision processing under stress. *Social Cognitive and Affective Neuroscience, 7*, 476–484. doi: 10.1093/scan/nsr026

Lin, C. H., Chiu, Y. C., Cheng, C. M., & Hsieh, J. C. (2008). Brain maps of Iowa Gambling Task. *BMC Neuroscience, 9*, 72. doi: 10.1186/1471-2202-9-72

Lineweaver, T. T., Bondi, M. W., Thomas, R. G., & Salmon, D. P. (1999). A normative study of Nelson's (1976) modified version of the Wisconsin Card Sorting Test in healthy older adults. *Clinical Neuropsychologist, 13*, 328–347. doi: 10.1076/clin.13.3.328.1745

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393–434. doi: 10.1037/0033-295x.108.2.393

Logie, R. H., Cocchini, G., Delia Sala, S., & Baddeley, A. D. (2004). Is there a specific executive capacity for dual task coordination? Evidence from Alzheimer's disease. *Neuropsychology, 18*, 504–513. doi: 10.1037/0894-4105.18.3.504

Lovallo, W. R., Farag, N. H., Vincent, A. S., Thomas, T. L., & Wilson, M. F. (2006). Cortisol responses to mental stress, exercise, and meals following caffeine intake in men and women. *Pharmacology Biochemistry and Behavior, 83*, 441–447. doi: 10.1016/j.pbb.2006.03.005

Lupien, S. J., Gillin, C. J., & Hauger, R. L. (1999). Working memory is more sensitive than declarative memory to the acute effects of corticosteroids: A dose-response study in humans. *Behavioral Neuroscience, 113*, 420–430. doi: 10.1037/0735-7044.113.3.420

Lupien, S. J., Maheu, F., Tu, M., Fiocco, A., & Schramek, T. E. (2007). The effects of stress and stress hormones on human cognition: Implications for the field of brain and cognition. *Brain and Cognition, 65*, 209–237. doi: 10.1016/j.bandc.2007.02.007

Lussier, M., Gagnon, C., & Bherer, L. (2012). An investigation of far response and stimulus modality transfer effects after dual-task training in younger and older adults. *Frontiers in Human Neuroscience, 6*, 129. doi: 10.3389/fnhum.2012.00129

Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: A review and future directions. *Neuropsychology Review, 19*, 504–522. doi: 10.1007/s11065-009-9119-9

Ma, H., Lv, X., Han, Y., Zhang, F., Ye, R., Yu, F., . . . Wang, K. (2013). Decision-making impairments in patients with Wilson's disease. *Journal of Clinical and Experimental Neuropsychology, 35*, 472–479. doi: 10.1080/13803395.2013.789486

MacDonald III, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*, 1835–1838. doi: 10.2307/3075438

MacLean, P. D. (1949). Psychosomatic disease and the "visceral brain": Recent developments bearing on the Papez theory of emotion. *Psychosomatic Medicine, 11*, 338–353.

Macmillan, M. (2000). Restoring Phineas Gage: A 150th retrospective. *Journal of the History of Neurosciences, 9*, 46–66. doi: 10.1076/0964-704X(200004)9:1;1-2;FT046

Madden, D. J., Turkington, T. G., Provenzale, J. M., Denny, L. L., Langley, L. K., Hawk, T. C., & Coleman, R. E. (2002). Aging and attentional guidance during visual search: Functional neuroanatomy by positron emission tomography. *Psychology and Aging, 17*, 24-43. doi: 10.1037/0882-7974.17.1.24

Maia, T. V., & McClelland, J. L. (2004). A reexamination of the evidence for the somatic marker hypothesis: What participants really know in the Iowa Gambling Task. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 16075–16080. doi: 10.1073/pnas.0406666101

Maldjian, J. A., Laurienti, P. J., & Burdette, J. H. (2004). Precentral gyrus discrepancy in electronic versions of the Talairach atlas. *NeuroImage, 21*, 450–455. doi: 10.1016/j.neuroimage.2003.09.032

Maldjian, J. A., Laurienti, P. J., Kraft, R. A., & Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *NeuroImage, 19*, 1233–1239. doi: 10.1016/s1053-8119(03)00169-1

Maner, J. K., Richey, J. A., Cromer, K., Mallott, M., Lejuez, C. W., Joiner, T. E., & Schmidt, N. B. (2007). Dispositional anxiety and risk-avoidant decision-making. *Personality and Individual Differences, 42*, 665–675. doi: 10.1016/j.paid.2006.08.016

Markowitsch, H. J. (1999). Limbic system. In R. Wilson & F. Keil (Eds.), *The MIT encyclopedia of the cognitive science* (pp. 472-475). Camebridge, MA: MIT Press.

Markowitsch, H. J. (2000). Strukturelle und funktionelle Neuroanatomie [Structural and functional neuroanatomy]. In W. Sturm, M. Herrmann & C. Wallesch (Eds.), *Lehrbuch der klinischen Neuropsychologie [Textbook of clinical neuropsychology]* (pp. 25-50). Amsterdam, Netherlands: Swets & Zeitlinger.

Martin, C. O., Denburg, N. L., Tranel, D., Granner, M. A., & Bechara, A. (2004). The effects of vagus nerve stimulation on decision-making. *Cortex, 40*, 605–612. doi: 10.1016/S0010-9452(08)70156-4

Martin, E. A., & Kerns, J. G. (2011). The influence of positive mood on different aspects of cognitive control. *Cognition and Emotion, 25*, 265–279. doi: 10.1080/02699931.2010.491652

Matrenza, C., Hughes, J.-M., Kemp, A. H., Wesnes, K. A., Harrison, B. J., & Nathan, P. J. (2004). Simultaneous depletion of serotonin and catecholamines impairs sustained attention in healthy female subjects without affecting learning and memory. *Journal of Psychopharmacology, 18*, 21–31. doi: 10.1177/0269881104040215

Matthies, S., Philipsen, A., & Svaldi, J. (2012). Risky decision making in adults with ADHD. *Journal of Behavior Therapy and Experimental Psychiatry, 43*, 938–946. doi: 10.1016/j.jbtep.2012.02.002

McClure, S. M., Laibson, D. I., Loewenstein, G., & Cohen, J. D. (2004). Separate neural systems value immediate and delayed monetary rewards. *Science, 306*, 503–507. doi: 10.1126/science.1100907

McDougall, W. (1908,1960). *An introduction to social psychology*. London, UK: Methuen.

McIntosh, A. R. (1998). Understanding neural interactions in learning and memory using functional neuroimaging. *Annals of the New York Academy of Sciences, 855*, 556–571. doi: 10.1111/j.1749-6632.1998.tb10625.x

McIntosh, A. R. (1999). Mapping cognition to the brain through neural interactions. *Memory, 7*, 523–548. doi: 10.1080/096582199387733

McIntosh, A. R., & Gonzalez-Lima, F. (1994). Structural equation modeling and its application to network analysis in functional brain imaging. *Human Brain Mapping, 2*, 2–22. doi: 10.1002/hbm.460020104

McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience, 11*, 103–107. doi: 10.1038/nn2024

McNab, F., Varrone, A., Farde, L., Jucaite, A., Bystritsky, P., Forssberg, H., & Klingberg, T. (2009). Changes in cortical dopamine D1 receptor binding associated with cognitive training. *Science, 323*, 800–802. doi: 10.1126/science.1166102

Mecklinger, A., von Cramon, D. Y., Springer, A., & Matthes-von Cramon, G. (1999). Executive control functions in task switching: Evidence from brain injured patients. *Journal of Clinical and Experimental Neuropsychology, 21*, 606–619. doi: 10.1076/jcen.21.5.606.873

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 22*, 1423–1442. doi: 10.1037/0278-7393.22.6.1423

Menon, R. S., Ogawa, S., Hu, X., Strupp, J. P., Anderson, P., & Uğurbil, K. (1995). BOLD based functional MRI at 4 tesla includes a capillary bed contribution: Echo-planar imaging correlates with previous optical imaging using intrinsic signals. *Magnetic Resonance in Medicine, 33*, 453–459. doi: 10.1002/mrm.1910330323

Mesulam, M. M. (1985). *Principles of behavioral neurology*. Philadelphia, PA: F. A. Davis Comp.

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104*, 3–65. doi: 10.1037/0033-295x.104.1.3

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104*, 749–791. doi: 10.1037/0033-295x.104.4.749

Meyer, W.-U., Schützwohl, A., & Reisenzein, R. (2001) Einführung in die Emotionspsychologie [Introduction into psychology of emotion]. *Vol. 1. Die Emotionstheorien von Watson, James und Schachter [Theories of emotion by Watson, James, and Schachter]* (2 ed.). Bern (u.a.), Switzerland: Verlag Hans Huber.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167–202. doi: 10.1146/annurev.neuro.24.1.167

Mitchell, K. J., Johnson, M. K., Raye, C. L., & D'Esposito, M. (2000). FMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. *Brain Research. Cognitive Brain Research, 10*, 197–206. doi: 10.1016/S0926-6410(00)00029-X

Mitchell, R. L. C., & Phillips, L. H. (2007). The psychological, neurochemical and functional neuroanatomical mediators of the effects of positive and negative mood on executive functions. *Neuropsychologia, 45*, 617–629. doi: 10.1016/j.neuropsychologia.2006.06.030

Miu, A. C., Heilman, R. M., & Houser, D. (2008). Anxiety impairs decision-making: Psychophysiological evidence from an Iowa Gambling Task. *Biological Psychology, 77*, 353–358. doi: 10.1016/j.biopsycho.2007.11.010

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science, 21*, 8–14. doi: 10.1177/0963721411429458.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100. doi: 10.1006/cogp.1999.0734

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93-148). Hove, UK: Erlbaum.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134–140. doi: 10.1016/S1364-6613(03)00028-7

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory and Cognition, 31*, 327–342. doi: 10.3758/bf03194391

Morgan, B., Terburg, D., Thornton, H. B., Stein, D. J., & Van Honk, J. (2012). Paradoxical facilitation of working memory after basolateral amygdala damage. *PLoS ONE, 7*, e38116. doi: 10.1371/journal.pone.0038116

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81*, 111–121. doi: 10.1111/j.2044-8295.1990.tb02349.x

Morrow, B. A., Roth, R. H., & Elsworth, J. D. (2000). TMT, a predator odor, elevates mesoprefrontal dopamine metabolic activity and disrupts short-term working memory in the rat. *Brain Research Bulletin, 52*, 519–523. doi: 10.1016/S0361-9230(00)00290-2

Mueller, V. A., Brass, M., Waszak, F., & Prinz, W. (2007). The role of the preSMA and the rostral cingulate zone in internally selected actions. *NeuroImage, 37*, 1354–1361. doi: 10.1016/j.neuroimage.2007.06.018

Müller, N. G., & Knight, R. T. (2006). The functional neuroanatomy of working memory: Contributions of human brain lesion studies. *Neuroscience, 139*, 51–58. doi: 10.1016/j.neuroscience.2005.09.018

Must, A., Szabó, Z., Bódi, N., Szász, A., Janka, Z., & Kéri, S. (2006). Sensitivity to reward and punishment and the prefrontal cortex in major depression. *Journal of Affective Disorders, 90*, 209–215. doi: 10.1016/j.jad.2005.12.005

Muthén, L. K., & Muthén, B. O. (2011). *Mplus user's guide* (6 ed.). Los Angeles, CA: Muthén & Muthén.

Nagahama, Y., Okada, T., Katsumi, Y., Hayashi, T., Yamauchi, H., Oyanagi, C., . . . Shibasaki, H. (2001). Dissociable mechanisms of attentional control within the human prefrontal cortex. *Cerebral Cortex, 11*, 85–92. doi: 10.1093/cercor/11.1.85

Naqvi, N., Shiv, B., & Bechara, A. (2006). The role of emotion in decision making. *Current Directions in Psychological Science, 15*, 260–264. doi: 10.1111/j.1467-8721.2006.00448.x

Nater, U. M., & Rohleder, N. (2009). Salivary alpha-amylase as a non-invasive biomarker for the sympathetic nervous system: Current state of research. *Psychoneuroendocrinology, 34*, 486–496. doi: 10.1016/j.psyneuen.2009.01.014

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review, 86*, 214–255. doi: 10.1037/0033-295x.86.3.214

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology. Human Perception and Performance, 13*, 435–448. doi: 10.1037/0096-1523.13.3.435

Nelson, H. E. (1976). A modified card sorting test sensitive to frontal lobe defects. *Cortex, 12*, 313–324.

Newcombe, V. F. J., Outtrim, J. G., Chatfield, D. A., Manktelow, A., Hutchinson, P. J., Coles, J. P., . . . Menon, D. K. (2011). Parcellating the neuroanatomical basis of impaired decision-making in traumatic brain injury. *Brain, 134*, 759–768. doi: 10.1093/brain/awq388

Noack, H., Lövdén, M., Schmiedek, F., & Lindenberger, U. (2009). Cognitive plasticity in adulthood and old age: Gauging the generality of cognitive intervention effects. *Restorative Neurology and Neuroscience, 27*, 435–453. doi: 10.3233/rnn-2009-0496

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7*, 44–64. doi: 10.1016/0010-0285(75)90004-3

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz & D. Shapiro (Eds.), *Consciousness and self-regulation: Advances in research and theory* (Vol. 4, pp. 1-18). New York, NY: Plenum.

North, N. T., & O'Carroll, R. E. (2001). Decision making in patients with spinal cord damage: Afferent feedback and the somatic marker hypothesis. *Neuropsychologia, 39*, 521–524.

Northoff, G., Grimm, S., Boeker, H., Schmidt, C., Bermpohl, F., Heinzel, A., . . . Boesiger, P. (2006). Affective judgment and beneficial decision making: Ventromedial prefrontal activity correlates with performance in the Iowa Gambling Task. *Human Brain Mapping, 27*, 572–587. doi: 10.1002/hbm.20202

Oaksford, M., Morris, F., Grainger, B., & Williams, J. M. G. (1996). Mood, reasoning, and central executive processes. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 22*, 476–492. doi: 10.1037/0278-7393.22.2.476

Oei, N., Elzinga, B., Wolf, O. T., Ruiter, M., Damoiseaux, J., Kuijer, J., . . . Rombouts, S. (2007). Glucocorticoids decrease hippocampal and prefrontal activation during declarative memory retrieval in young men. *Brain Imaging and Behavior, 1*, 31–41. doi: 10.1007/s11682-007-9003-2

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences of the United States of America, 87*, 9868–9872.

Ogawa, S., Menon, R. S., Tank, D. W., Kim, S. G., Merkle, H., Ellermann, J. M., & Ugurbil, K. (1993). Functional brain mapping by blood oxygenation level-dependent contrast magnetic resonance imaging. A comparison of signal characteristics with a biophysical model. *Biophysical Journal, 64*, 203–812. doi: 10.1016/S0006-3495(93)81441-3

Öhman, A. (2002). Automaticity and the amygdala: Nonconscious responses to emotional faces. *Current Directions in Psychological Science, 11*, 62–66. doi: 10.1111/1467-8721.00169

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7*, 75–79. doi: 10.1038/nn1165

Otsuka, Y., Osaka, N., Morishita, M., Kondo, H., & Osaka, M. (2006). Decreased activation of anterior cingulate cortex in the working memory of the elderly. *Neuroreport, 17*, 1479–1482. doi: 10.1097/01.wnr.0000236852.63092.9f

Owen, A. M., Downes, J. J., Sahakian, B. J., Polkey, C. E., & Robbins, T. W. (1990). Planning and spatial working memory following frontal lobe lesions in man. *Neuropsychologia, 28*, 1021–1034. doi: 10.1016/0028-3932(90)90137-D

Owen, A. M., Doyon, J., Petrides, M., & Evans, A. C. (1990). Planning and spatial working memory: A positron emission tomography study in humans. *European Journal of Neuroscience, 8*, 353–364. doi: 10.1111/j.1460-9568.1996.tb01219.x

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-Back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 25*, 46–59. doi: 10.1002/hbm.20131

Pabst, S., Brand, M., & Wolf, O. T. (2013). Stress and decision making: A few minutes make all the difference. *Behavioural Brain Research, 250*, 39–45. doi: 10.1016/j.bbr.2013.04.046

Pabst, S., Schoofs, D., Pawlikowski, M., Brand, M., & Wolf, O. T. (2013). Paradoxical effects of stress and an executive task on decisions under risk. *Behavioral Neuroscience*, 369–379. doi: 10.1037/a0032334

Papez, J. W. (1937). A proposed mechanism of emotion. *Archives of Neurology and Psychiatry, 38*, 725–743. doi: 10.1001/archneurpsyc.1937.02260220069003

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology. Human Perception and Performance, 10*, 358–377. doi: 10.1037/0096-1523.10.3.358

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244. doi: 10.1037/0033-2909.116.2.220

Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

Passetti, F., Clark, L., Mehta, M. A., Joyce, E., & King, M. (2008). Neuropsychological predictors of clinical outcome in opiate addiction. *Drug and Alcohol Dependence, 94*, 82–91. doi: 10.1016/j.drugalcdep.2007.10.008

Paulesu, E., Frith, C. D., & Frackowiak, R. S. J. (1993). The neural correlates of the verbal component of working memory. *Nature, 362*, 342–345. doi: 10.1038/362342a0

Pennington, B. F., Bennetto, L., McAleer, O., & Roberts, R. J. (1996). Executive functions and working memory: Theoretical and measurement issues. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 327-348). Baltimore, MD: Paul H. Brooks Publishing.

Perlstein, W. M., Elbert, T., & Stenger, V. A. (2002). Dissociation in human prefrontal cortex of affective influences on working memory-related activity. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 1736–1741. doi: 10.1073/pnas.241650598

Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of arabic number processing, numerical comparison, and simple addition: A PET Study. *Journal of Cognitive Neuroscience, 12*, 461–479. doi: 10.1162/089892900562273

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature Reviews. Neuroscience, 9*, 148–158. doi: 10.1038/nrn2317

Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Sciences, 13*, 160–166. doi: 10.1016/j.tics.2009.01.006

Pessoa, L., McKenna, M., Gutierrez, E., & Ungerleider, L. G. (2002). Neural processing of emotional faces requires attention. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 11458–11463. doi: 10.1073/pnas.172403899

Phelps, E. A., & LeDoux, J. E. (2005). Contributions of the amygdala to emotion processing: From animal models to human behavior. *Neuron, 48*, 175–187. doi: 10.1016/j.neuron.2005.09.025

Phillips, L. H., Bull, R., Adams, E., & Fraser, L. (2002). Positive mood and executive function: Evidence from Stroop and fluency tasks. *Emotion, 2*, 12–22. doi: 10.1037/1528-3542.2.1.12

Pinel, J. P. J. (2001). Biopsychologie [Biological psychology]. W. Bouscein (Ed.). Heidelberg [etc.], Germany: Spektrum akademischer Verlag.

Plessow, F., Fischer, R., Kirschbaum, C., & Goschke, T. (2011). Inflexibly focused under stress: Acute psychosocial stress increases shielding of action goals at the expense of reduced cognitive flexibility with increasing time lag to the stressor. *Journal of Cognitive Neuroscience, 23*, 3218–3227. doi: 10.1162/jocn_a_00024

Plessow, F., Schade, S., Kirschbaum, C., & Fischer, R. (2012). Better not to deal with two tasks at the same time when stressed? Acute psychosocial stress reduces task shielding in dual-task performance. *Cognitive, Affective, & Behavioral Neuroscience, 12*, 557–570. doi: 10.3758/s13415-012-0098-6

Plutchik, R. (1962). *The emotions: Facts, theories, and a new model*. New York, NY: Random House.

Porcelli, A. J., & Delgado, M. R. (2009). Acute stress modulates risk taking in financial decision making. *Psychological Science, 20*, 278–283. doi: 10.1111/j.1467-9280.2009.02288.x

Poser, B. A., Koopmans, P. J., Witzel, T., Wald, L. L., & Barth, M. (2010). Three dimensional echo-planar imaging at 7 Tesla. *NeuroImage, 51*, 261–266. doi: 10.1016/j.neuroimage.2010.01.108

Power, Y., Goodyear, B., & Crockford, D. (2012). Neural correlates of pathological gamblers preference for immediate rewards during the Iowa Gambling Task: An fMRI study. *Journal of Gambling Studies, 28*, 623–636. doi: 10.1007/s10899-011-9278-5

Preston, S. D., Buchanan, T. W., Stansfield, R. B., & Bechara, A. (2007). Effects of anticipatory stress on decision making in a gambling task. *Behavioral Neuroscience, 121*, 257–263. doi: 10.1037/0735-7044.121.2.257

Pritzel, M., Brand, M., & Markowitsch, H. J. (2003). Gehirn und Verhalten. Ein Grundkurs der physiologischen Psychologie [Brain and behavior. A basic class of physiological psychology]. Heidelberg [etc], Germany: Spektrum Akademischer Verlag.

Pruessner, J. C., Dedovic, K., Khalili-Mahani, N., Engert, V., Pruessner, M., Buss, C., . . . Lupien, S. (2008). Deactivation of the limbic system during acute psychosocial stress: Evidence from positron emission tomography and functional magnetic resonance imaging studies. *Biological Psychiatry, 63*, 234–240. doi: 10.1016/j.biopsych.2007.04.041

Putman, P., Antypa, N., Crysovergi, P., & van der Does, W. (2010). Exogenous cortisol acutely influences motivated decision making in healthy young men. *Psychopharmacology, 208*, 257–263. doi: 10.1007/s00213-009-1725-y

Putman, P., Hermans, E. J., & van Honk, J. (2010). Cortisol administration acutely reduces threat-selective spatial attention in healthy young men. *Physiology and Behavior, 99*, 294–300. doi: 10.1016/j.physbeh.2009.11.006

Qin, S., Hermans, E. J., van Marle, H. J. F., Luo, J., & Fernández, G. (2009). Acute psychological stress reduces working memory-related activity in the dorsolateral prefrontal cortex. *Biological Psychiatry, 66*, 25–32. doi: 10.1016/j.biopsych.2009.03.006

Rao, H., Korczykowski, M., Pluta, J., Hoang, A., & Detre, J. A. (2008). Neural correlates of voluntary and involuntary risk taking in the human brain: An fMRI study of the Balloon Analog Risk Task (BART). *NeuroImage, 42*, 902–910. doi: 10.1016/j.neuroimage.2008.05.046

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *Handbook of aging and cognition* (pp. 1-90). Mahwah, NJ: Lawrence Erlbaum Associations.

Reddy, L. F., Lee, J., Davis, M. C., Altshuler, L., Glahn, D. C., Miklowitz, D. J., & Green, M. F. (2014). Impulsivity and risk taking in bipolar disorder and schizophrenia. *Neuropsychopharmacology, 39*, 456–463. doi: 10.1038/npp.2013.218

Reisenzein, R., & Gattinger, E. (1982). Salience of arousal as a mediator of misattribution of transferred excitation. *Motivation and Emotion, 6*, 315–328. doi: 10.1007/bf00998188

Reyna, V. F. (2004). How people make decisions that involve risk: A dual-processes approach. *Current Directions in Psychological Science, 13*, 60–66. doi: 10.1111/j.0963-7214.2004.00275.x

Rogers, R. D., Everitt, B. J., Baldacchino, A., Blackshaw, A. J., Swainson, R., Wynne, K., . . . Robbins, T. W. (1999). Dissociable deficits in the decision-making cognition of chronic amphetamine abusers, opiate abusers, patients with focal damage to prefrontal cortex, and tryptophan-depleted normal volunteers: Evidence for monoaminergic mechanisms. *Neuropsychopharmacology, 20*, 322–339. doi: 10.1016/S0893-133X%2898%2900091-8

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology. General, 124*, 207–231. doi: 10.1037/0096-3445.124.2.207

Rogers, R. D., Owen, A. M., Middleton, H. C., Williams, E. J., Pickard, J. D., Sahakian, B. J., & Robbins, T. W. (1999). Choosing between small, likely rewards and large, unlikely rewards activates inferior and orbital prefrontal cortex. *Journal of Neuroscience, 19*, 9029–9038.

Rogers, R. D., Ramnani, N., Mackay, C., Wilson, J. L., Jezzard, P., Carter, C. S., & Smith, S. M. (2004). Distinct portions of anterior cingulate cortex and medial prefrontal cortex are activated by reward processing in separable phases of decision-making cognition. *Biological Psychiatry, 55*, 594–602. doi: 10.1016/j.biopsych.2003.11.012

Rohleder, N., & Nater, U. M. (2009). Determinants of salivary alpha-amylase in humans and methodological considerations. *Psychoneuroendocrinology, 34*, 469–485. doi: 10.1016/j.psyneuen.2008.12.004

Roiser, J. P., Cannon, D. M., Gandhi, S. K., Tavares, J. T., Erickson, K., Wood, S., . . . Drevets, W. C. (2009). Hot and cold cognition in unmedicated depressed subjects with bipolar disorder. *Bipolar Disorders, 11*, 178–189. doi: 10.1111/j.1399-5618.2009.00669.x

Rolls, E. T. (1990). A theory of emotion, and its application to understanding the neural basis of emotion. *Cognition and Emotion, 4*, 161–190. doi: 10.1080/02699939008410795

Rolls, E. T. (2000). The orbitofrontal cortex and reward. *Cerebral Cortex, 10*, 284–294. doi: 10.1093/cercor/10.3.284

Rolls, E. T. (2014). *Emotion and decision-making explained*. Oxford, UK: Oxford University Press.

Rolls, E. T. (in press). Limbic systems for emotion and for memory, but no single limbic system. *Cortex*. doi: 10.1016/j.cortex.2013.12.005

Romer, D., & Hennessy, M. (2007). A biosocial-affect model of adolescent sensation seeking: The role of affect evaluation and peer-group influence in adolescent drug use. *Prevention Science, 8*, 89–101. doi: 10.1007/s11121-007-0064-7

Roozendaal, B., McEwen, B. S., & Chattarji, S. (2009). Stress, memory and the amygdala. *Nature Reviews. Neuroscience, 10*, 423–433. doi: 10.1038/nrn2651

Rorden, C., Karnath, H.-O., & Bonilha, L. (2007). Improving lesion-symptom mapping. *Journal of Cognitive Neuroscience, 19*, 1081–1088. doi: 10.1162/jocn.2007.19.7.1081

Royall, D. R., Lauterbach, E. C., Cummings, J. L., Reeve, A., Rummans, T. A., Kaufer, D. I., . . . Coffey, C. E. (2002). Executive control function: A review of its promise and challenges for clinical research. *Journal of Neuropsychiatry and Clinical Neurosciences, 14*, 377–405. doi: 10.1176/appi.neuropsych.14.4.377

Rubinsztein, J. S., Fletcher, P. C., Rogers, R. D., Ho, L. W., Aigbirhio, F. I., Paykel, E. S., . . . Sahakian, B. J. (2001). Decision-making in mania: A PET study. *Brain, 124*, 2550–2563. doi: 10.1093/brain/124.12.2550

Rypma, B., & D'Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience, 3*, 509–515. doi: 10.1038/74889

Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology. General, 132*, 566–594. doi: 10.1037/0096-3445.132.4.566

Sapolsky, R. M., Romero, L. M., & Munck, A. U. (2000). How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. *Endocrine Reviews, 21*, 55–89. doi: 10.1210/er.21.1.55

Sarter, M., & Markowitsch, H. J. (1985). The amygdala's role in human mnemonic processing. *Cortex, 21*, 7–24. doi: 10.1016/S0010-9452(85)80013-7

Saver, J. L., & Damasio, A. R. (1991). Preserved access and processing of social knowledge in a patient with acquired sociopathy due to ventromedial frontal damage. *Neuropsychologia, 29*, 1241–1249. doi: 10.1016/0028-3932(91)90037-9

Schachter, S. (1964). The interaction of cognitive and physiological determinants of emotional states. In L. Berkowitz (Ed.), *Advances in experimental social psychology* (pp. 49-81). New York, NY: Academic Press, Inc.

Schachter, S., & Singer, J. (1962). Cognitive, social, and physiological determinants of emotional state. *Psychological Review, 69*, 379–399. doi: 10.1037/h0046234

Schacter, D. L., & Wagner, A. D. (1999). Medial temporal lobe activations in fMRI and PET studies of episodic encoding and retrieval. *Hippocampus, 9*, 7–24. doi: 10.1002/(sici)1098-1063(1999)9:1<7::aid-hipo2>3.0.co;2-k

Schaefer, A., Braver, T. S., Reynolds, J. R., Burgess, G. C., Yarkoni, T., & Gray, J. R. (2006). Individual differences in amygdala activity predict response speed during working memory. *Journal of Neuroscience, 26*, 10120–10128. doi: 10.1523/jneurosci.2567-06.2006

Schaefer, A., & Gray, J. R. (2007). A role for the human amygdala in higher cognition. *Reviews in the Neurosciences, 18*, 355–364. doi: 10.1515/REVNEURO.2007.18.5.355

Schär, M., Kozerke, S., Fischer, S. E., & Boesiger, P. (2004). Cardiac SSFP imaging at 3 Tesla. *Magnetic Resonance in Medicine, 51*, 799–806. doi: 10.1002/mrm.20024

Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). Evaluating the fit of structural equation models: Tests of significance and descriptive goodness-of-fit measures. *Methods of Psychological Reserach Online, 8*, 23–74.

Schiebener, J., Staschkiewicz, B., & Brand, M. (2013). The neuropsychology of emotional and cognitive mechanisms in decision making. In C. Mohiyeddini, M. Eysenck & S. Bauer (Eds.), *Handbook of psychology of emotions: Recent theoretical perspectives and novel empirical findings* (Vol. 2, pp. 201-244). New York, NY: Nova Science Publishers.

Schiebener, J., Wegmann, E., Pawlikowski, M., & Brand, M. (2012). Anchor effects in decision making can be reduced by the interaction between goal monitoring and the level of the decision maker's executive functions. *Cognitive Processing, 13*, 321–332. doi: 10.1007/s10339-012-0522-4

Schiebener, J., Wegmann, E., Pawlikowski, M., & Brand, M. (2013). Supporting decisions under risk: Explicit advice differentially affects people according to their working memory performance and executive functioning. *Neuroscience of Decision Making, 1*, 9–18. doi: 10.2478/ndm-2013-0002,

Schiebener, J., Wegmann, E., Pawlikowski, M., & Brand, M. (2014). Effects of goals on decisions under risk conditions: Goals can help to make better choices, but relatively high goals increase risk-taking. *Journal of Cognitive Psychology, 26*, 473–485. doi: 10.1080/20445911.2014.903254

Schiebener, J., Zamarian, L., Delazer, M., & Brand, M. (2011). Executive functions, categorization of probabilities, and learning from feedback: What does really matter for decision making under explicit risk conditions? *Journal of Clinical and Experimental Neuropsychology, 33*, 1025–1039. doi: 10.1080/13803395.2011.595702

Schoofs, D., Preuß, D., & Wolf, O. T. (2008). Psychosocial stress induces working memory impairments in an n-back paradigm. *Psychoneuroendocrinology, 33*, 643–653. doi: 10.1016/j.psyneuen.2008.02.004

Schubert, T., & Szameitat, A. J. (2003). Functional neuroanatomy of interference in overlapping dual tasks: An fMRI study. *Brain Research. Cognitive Brain Research, 17*, 733–746. doi: 10.1016/S0926-6410(03)00198-8

Schultz, W., Tremblay, L., & Hollerman, J. R. (2000). Reward processing in primate orbitofrontal cortex and basal ganglia. *Cerebral Cortex, 10*, 272–283. doi: 10.1093/cercor/10.3.272

Schwabe, L., Schächinger, H., de Kloet, E. R., & Oitzl, M. S. (2010). Corticosteroids operate as a switch between memory systems. *Journal of Cognitive Neuroscience, 22*, 1362–1372. doi: 10.1162/jocn.2009.21278

Schwabe, L., Wolf, O. T., & Oitzl, M. S. (2010). Memory formation under stress: Quantity and quality. *Neuroscience and Biobehavioral Reviews, 34*, 584–591. doi: 10.1016/j.neubiorev.2009.11.015

Scornaiencki, R., Cantrup, R., Rushlow, W. J., & Rajakumar, N. (2009). Prefrontal cortical D1 dopamine receptors modulate subcortical D2 dopamine receptor-mediated stress responsiveness. *International Journal of Neuropsychopharmacology, 12*, 1195–1208. doi: 10.1017/S1461145709000121

Seamans, J. K., & Yang, C. R. (2004). The principal features and mechanisms of dopamine modulation in the prefrontal cortex. *Progress in Neurobiology, 74*, 1–58. doi: 10.1016/j.pneurobio.2004.05.006

Selye, H. (1956). *Stress of life*. New York, NY: McGraw-Hill.

Selye, H. (1976). *Stress in health and disease*. Boston, MA: Butterworths.

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 298*, 199–209. doi: 10.1098/rstb.1982.0082

Shallice, T. (2002). Fractionation of the supervisory system. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 261-277). New York, NY: Oxford University Press.

Shallice, T., Burgess, P., & Robertson, I. (1996). The domain of supervisory processes and temporal organization of behaviour. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 351*, 1405–1412. doi: 10.1098/rstb.1996.0124

Shallice, T., & Burgess, P. W. (1991a). Deficits in strategy application following frontal lobe damage in man. *Brain, 114*, 727–741. doi: 10.1093/brain/114.2.727

Shallice, T., & Burgess, P. W. (1991b). Higher-order cognitive impairments and frontal lobe lesions in man. In H. S. Levin, H. M. Eisenberg & A. L. Benton (Eds.), *Frontal lobe and dysfunction* (pp. 125-138). New York, NY: Oxford University Press.

Shallice, T., Stuss, D. T., Picton, T. W., Alexander, M. P., & Gillingham, S. (2008). Mapping task switching in frontal cortex through neuropsychological group studies. *Frontiers in Neuroscience, 2*, 79–85. doi: 10.3389/neuro.01.013.2008

Simoni, S., Schlueo, M., Bault, N., Coricelli, G., Kleeberg, J., Du Pasquier, R. A., . . . Annoni, J.-M. (2012). Multiple sclerosis decreases explicit counterfactual processing and risk taking in decision making. *PLoS ONE, 7*, e50718. doi: 10.1371/journal.pone.0050718.

Sinz, H., Zamarian, L., Benke, T., Wenning, G. K., & Delazer, M. (2008). Impact of ambiguity and risk on decision making in mild Alzheimer's disease. *Neuropsychologia, 46*, 2043–2055. doi: 10.1016/j.neuropsychologia.2008.02.002

Slovic, P., Finucane, M. L., Peters, E., & MacGregor, D. G. (2004). Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk, and rationality. *Risk Analysis, 24*, 311–322. doi: 10.1111/j.0272-4332.2004.00433.x

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33*, 5–42. doi: 10.1006/cogp.1997.0658

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*, 1657–1661. doi: 10.1126/science.283.5408.1657

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*, 11–20. doi: 10.1093/cercor/6.1.11

Smith, E. E., Jonides, J., Koeppe, R. A., Awh, E., Schumacher, E., & Minoshima, S. (1995). Spatial versus object working memory: PET investigations. *Journal of Cognitive Neuroscience, 7*, 337–356. doi: 10.1162/jocn.1995.7.3.337

Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin, 67*, 202–213. doi: 10.1037/h0020419

Smoski, M. J., Lynch, T. R., Rosenthal, M. Z., Cheavens, J. S., Chapman, A. L., & Krishnan, R. R. (2008). Decision-making and risk aversion among depressive adults. *Journal of Behavior Therapy and Experimental Psychiatry, 39*, 567–576. doi: 10.1016/j.jbtep.2008.01.004

Sokolowski, K. (2008). Emotion [Emotion]. In J. Müsseler (Ed.), *Allgemeine Psychologie [General psychology]* (2 ed., pp. 337-384). Berlin, Germany: Spektrum Akademischer Verlag.

Soon, C. S., Brass, M., Heinze, H.-J., & Haynes, J.-D. (2008). Unconscious determinants of free decisions in the human brain. *Nature Neuroscience, 11*, 543–545. doi: 10.1038/nn.2112

Soufer, R., Bremner, J. D., Arrighi, J. A., Cohen, I., Zaret, B. L., Burg, M. M., & Goldman-Rakic, P. S. (1998). Cerebral cortical hyperactivation in response to mental stress in patients with coronary artery disease. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 6454–6459.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology, 89*, 669–679. doi: 10.2307/1421465

Spielberger, C. D., Gorsuch, R. L., Lushene, R. E., Vagg, P. R., & Jacobs, G. A. (1977). *Stait-Trait Anxiety Inventory for adults*. Redwood City, CA: Mind Garden.

Spies, K., Hesse, F., & Hummitzsch, C. (1996). Mood and capacity in Baddeley's model of human memory. *Zeitschrift für Psychologie mit Zeitschrift für angewandte Psychologie, 204*, 367–381.

Ståhle, L., Ståhle, E. L., Granström, E., Isaksson, S., Annas, P., & Sepp, H. (2011). Effects of sleep or food deprivation during civilian survival training on cognition, blood glucose and 3-OH-butyrate. *Wilderness and Environmental Medicine, 22*, 202–210. doi: 10.1016/j.wem.2011.02.018

Stanescu-Cosson, R., Pinel, P., van de Moortele, P.-F., Le Bihan, D., Cohen, L., & Dehaene, S. (2000). Understanding dissociations in dyscalculia. *Brain, 123*, 2240–2255. doi: 10.1093/brain/123.11.2240

Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience and Biobehavioral Reviews, 36*, 1228–1248. doi: 10.1016/j.neubiorev.2012.02.003

Starcke, K., Pawlikowski, M., Wolf, O. T., Altstötter-Gleich, C., & Brand, M. (2011). Decision-making under risk conditions is susceptible to interference by a secondary executive task. *Cognitive Processing, 12*, 177–182. doi: 10.1007/s10339-010-0387-3

Starcke, K., Tuschen-Caffier, B., Markowitsch, H. J., & Brand, M. (2009). Skin conductance responses during decisions in ambiguous and risky situations in obsessive-compulsive disorder. *Cognitive Neuropsychiatry, 14*, 199–216. doi: 10.1080/13546800902996831

Starcke, K., Wolf, O. T., Markowitsch, H. J., & Brand, M. (2008). Anticipatory stress influences decision making under explicit risk conditions. *Behavioral Neuroscience, 122*, 1352–1360. doi: 10.1037/a0013281

Steptoe, A., Fieldman, G., Evans, O., & Perry, L. (1996). Cardiovascular risk and responsivity to mental stress: The influence of age, gender and risk factors. *Journal of Cardiovascular Risk, 3*, 83–93. doi: 10.1177/174182679600300112

Stippich, C. (2007). Introduction to presurgical functional MRI. In C. Stippich (Ed.), *Clinical functional MRI: Presurgical functional neuroimaging* (pp. 1-7). Berlin [etc], Germany: Springer.

Strauss, E., Sherman, E. M. S., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms and commentary* (3 ed.). New York, NY: Oxford University Press.

Strobach, T., Frensch, P. A., Soutschek, A., & Schubert, T. (2012). Investigation on the improvement and transfer of dual-task coordination skills. *Psychological Research, 76*, 794-811. doi: 10.1007/s00426-011-0381-0

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

Stuss, D. T., & Alexander, M. P. (2000). Executive functions and the frontal lobes: A conceptual view. *Psychological Research, 63*, 289–298. doi: 10.1007/s004269900007

Stuss, D. T., & Benson, D. F. (1984). Neuropsychological studies of the frontal lobes. *Psychological Bulletin, 95*, 3–28. doi: 10.1037/0033-2909.95.1.3

Stuss, D. T., Gow, C. A., & Hetherington, C. R. (1992). 'No longer gage': Frontal lobe dysfunction and emotional changes. *Journal of Consulting and Clinical Psychology, 60*, 349–359. doi: 10.1037/0022-006x.60.3.349

Stuss, D. T., Shallice, T., Alexander, M. P., & Picton, T. W. (1995). A multidisciplinary approach to anterior attentional functions. *Annals of the New York Academy of Sciences, 769*, 191–212. doi: 10.1111/j.1749-6632.1995.tb38140.x

Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology. Human Perception and Performance, 13*, 89–103. doi: 10.1037/0096-1523.13.1.89

Suhr, J. A., & Tsanadis, J. (2007). Affect and personality correlates of the Iowa Gambling Task. *Personality and Individual Differences, 43*, 27–36. doi: 10.1016/j.paid.2006.11.004

Suzuki, A., Hirota, A., Takasawa, N., & Shigemasu, K. (2003). Application of the somatic marker hypothesis to individual differences in decision making. *Biological Psychology, 65*, 81–88. doi: 10.1016/S0301-0511%2803%2900093-0

Svaldi, J., Brand, M., & Tuschen-Caffier, B. (2010). Decision-making impairments in women with binge eating disorder. *Appetite, 54*, 84–92. doi: 10.1016/j.appet.2009.09.010

Svaldi, J., Philipsen, A., & Matthies, S. (2012). Risky decision-making in borderline personality disorder. *Psychiatry Research, 197*, 112–118. doi: 10.1016/j.psychres.2012.01.014

Szameitat, A. J., Lepsien, J., von Cramon, D. Y., Sterr, A., & Schubert, T. (2006). Task-order coordination in dual-task performance and the lateral prefrontal cortex: An event-related fMRI study. *Psychological Research, 70*, 541–552. doi: 10.1007/s00426-005-0015-5

Szameitat, A. J., Schubert, T., & Müller, H. J. (2011). How to test for dual-task-specific effects in brain imaging studies - An evaluation of potential analysis methods. *NeuroImage, 54*, 1765–1773. doi: 10.1016/j.neuroimage.2010.07.069

Szameitat, A. J., Schubert, T., Müller, K., & von Cramon, D. Y. (2002). Localization of executive functions in dual-task performance with fMRI. *Journal of Cognitive Neuroscience, 14*, 1184–1199. doi: 10.1162/089892902760807195

Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain*. New York, NY: Thieme

Talati, A., & Hirsch, J. (2005). Functional specialization within the medial frontal gyrus for perceptual Go/No-Go decisions based on "what," "when," and "where" related information: An fMRI study. *Journal of Cognitive Neuroscience, 17*, 981–993. doi: 10.1162/0898929054475226

Tchanturia, K., Liao, P.-C., Uher, R., Lawrence, N., Treasure, J., & Campbell, I. C. (2007). An investigation of decision making in anorexia nervosa using the Iowa Gambling Task and skin conductance measurements. *Journal of the International Neuropsychological Society, 13*, 635–641. doi: 10.1017/S1355617707070798

Tessner, K. D., Walker, E. F., Hochman, K., & Hamann, S. (2006). Cortisol responses of healthy volunteers undergoing magnetic resonance imaging. *Human Brain Mapping, 27*, 889–895. doi: 10.1002/hbm.20229

Thierry, A. M., Tassin, J. P., Blanc, G., & Glowinski, J. (1976). Selective activation of the mesocortical DA system by stress. *Nature, 263*, 242–244. doi: 10.1038/263242a0

Thürling, M., Hautzel, H., Küper, M., Stefanescu, M. R., Maderwald, S., Ladd, M. E., & Timmann, D. (2012). Involvement of the cerebellar cortex and nuclei in verbal and visuospatial working memory: A 7T fMRI study. *NeuroImage, 62*, 1537–1550. doi: 10.1016/j.neuroimage.2012.05.037

Tillfors, M., Furmark, T., Marteinsdottir, I., Fischer, H., Pissiota, A., Langstrom, B., & Fredrikson, M. (2001). Cerebral blood flow in subjects with social phobia during stressful speaking tasks: A PET study. *American Journal of Psychiatry, 158*, 1220–1226. doi: 10.1176/appi.ajp.158.8.1220

Tillfors, M., Furmark, T., Marteinsdottir, I., & Fredrikson, M. (2002). Cerebral blood flow during anticipation of public speaking in social phobia: A PET study. *Biological Psychiatry, 52*, 1113–1119. doi: 10.1016/s0006-3223(02)01396-3

Toplak, M. E., Sorge, G. B., Benoit, A., West, R. F., & Stanovich, K. E. (2010). Decision-making and cognitive abilities: A review of associations between Iowa Gambling Task performance, executive functions, and intelligence. *Clinical Psychology Review, 30*, 562–581. doi: 10.1016/j.cpr.2010.04.002

Torta, D. M. E., Castelli, L., Zibetti, M., Lopiano, L., & Geminiani, G. (2009). On the role of dopamine replacement therapy in decision-making, working memory, and reward in Parkinson's disease: Does the therapy-dose matter? *Brain and Cognition, 71*, 84–91. doi: 10.1016/j.bandc.2009.04.003

Tranel, D., Damasio, H., & Damasio, A. R. (1995). Double dissociation between overt and covert face recognition. *Journal of Cognitive Neuroscience, 7*, 425–432. doi: 10.1162/jocn.1995.7.4.425

Tsukada, H., Ohba, H., Nishiyama, S., & Kakiuchi, T. (2011). Differential effects of stress on [11C]raclopride and [11C]MNPA binding to striatal D2/D3 dopamine receptors: A PET study in conscious monkeys. *Synapse, 65*, 84–89. doi: 10.1002/syn.20845

Turnbull, O. H., Evans, C. E. Y., Bunce, A., Carzolio, B., & O'Connor, J. (2005). Emotion-based learning and central executive resources: An investigation of intuition and the Iowa Gambling Task. *Brain and Cognition, 57*, 244–247. doi: 10.1016/j.bandc.2004.08.053

Tversky, A., & Kahneman, D. (1971). Belief in the law of small numbers. *Psychological Bulletin, 76*, 105–110. doi: 10.1037/h0031322

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science, 185*, 1124–1131. doi: 10.1126/science.185.4157.1124

Vaidya, J. G., Block, R. I., O'Leary, D. S., Ponto, L. B., Ghoneim, M. M., & Bechara, A. (2012). Effects of chronic marijuana use on brain activity during monetary decision-making. *Neuropsychopharmacology, 37*, 618–629. doi: 10.1038/npp.2011.227

Van den Bos, R., Harteveld, M., & Stoop, H. (2009). Stress and decision-making in humans: Performance is related to cortisol reactivity, albeit differently in men and women. *Psychoneuroendocrinology, 34*, 1449–1458. doi: 10.1016/j.psyneuen.2009.04.016

Van den Eynde, F., Samarawickrema, N., Kenyon, M., DeJong, H., Lavender, A., Startup, H., & Schmidt, U. (2011). A study of neurocognition in bulimia nervosa and eating disorder not otherwise specified–bulimia type. *Journal of Clinical and Experimental Neuropsychology, 34*, 67–77. doi: 10.1080/13803395.2011.621891

Van Snellenberg, J. X., Whitman, J., McDonald, J. J., & Liotti, M. (2007). High temporal resolution imaging of spatial working memory. *International Congress Series, 1300*, 433–436. doi: 10.1016/j.ics.2007.02.037

Velten Jr, E. (1968). A laboratory task for induction of mood states. *Behaviour Research and Therapy, 6*, 473–482. doi: 10.1016/0005-7967(68)90028-4

Verdejo-García, A., Rivas-Pérez, C., Vilar-López, R., & Pérez-García, M. (2007). Strategic self-regulation, decision-making and emotion processing in poly-substance abusers in their first year of abstinence. *Drug and Alcohol Dependence, 86*, 139–146. doi: 10.1016/j.drugalcdep.2006.05.024

Volkow, N. D., Logan, J., Fowler, J. S., Wang, G.-J., Gur, R. C., Wong, C., . . . Pappas, N. (2000). Association between age-related decline in brain dopamine activity and impairment in frontal and cingulate metabolism. *American Journal of Psychiatry, 157*, 75–80. doi: 10.1176/appi.ajp.157.10.1709

Voytek, B., & Knight, R. T. (2010). Prefrontal cortex and basal ganglia contributions to visual working memory. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 18167–18172. doi: 10.2307/25748457

Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. *Trends in Cognitive Sciences, 9*, 585–594. doi: 10.1016/j.tics.2005.10.011

Wagar, B., & Dixon, M. (2006). Affective guidance in the Iowa gambling task. *Cognitive, Affective, & Behavioral Neuroscience, 6*, 277–290. doi: 10.3758/cabn.6.4.277

Wager, T. D., Hernandez, L., Jonides, J., & Lindquist, M. (2007). Elements of functional neuroimaging. In J. T. Cacioppo, L. G. Tassinary & G. G. Bernston (Eds.), *Handbook of psychophysiology* (3 ed., pp. 19-55). New York, NY: Cambridge University Press.

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory. *Cognitive, Affective, & Behavioral Neuroscience, 3*, 255–274. doi: 10.3758/cabn.3.4.255

Wand, G. S., Oswald, L. M., McCaul, M. E., Wong, D. F., Johnson, E., Zhou, Y., . . . Kumar, A. (2007). Association of amphetamine-induced striatal dopamine release and cortisol responses to psychological stress. *Neuropsychopharmacology, 32*, 2310–2320. doi: 10.1038/sj.npp.1301373

Wang, J., Rao, H., Wetmore, G. S., Furlan, P. M., Korczykowski, M., Dinges, D. F., & Detre, J. A. (2005). Perfusion functional MRI reveals cerebral blood flow pattern under psychological stress. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 17804–17809. doi: 10.1073/pnas.05803082102

Watkins, L. H. A., Rogers, R. D., Lawrence, A. D., Sahakian, B. J., Rosser, A. E., & Robbins, T. W. (2000). Impaired planning but intact decision making in early Huntington's disease: Implications for specific fronto-striatal pathology. *Neuropsychologia, 38*, 1112–1125. doi: 10.1016/S0028-3932(00)00028-2

Watson, D., & Clark, L. A. (1999). *PANAS-X. Manual for the Positive and Negative Affect Schedule - Expanded form*. Ames, IA: The University of Iowa.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*, 1063–1070. doi: 10.1037/0022-3514.54.6.1063

Weber, E. U., & Johnson, E. J. (2009). Decision under uncertainty: Psychological, economic and neuroeconomic explanations of risk preference. In P. W. Glimscher, C. F. Camerer, E. Fehr & R. A. Poldrack (Eds.), Neuroeconomics: Decision making and the brain (pp. 127-144). Amsterdam [etc], Netherlands: Elsevier. doi: 10.1016/B978-0-12-374176-9.00010-5

Welford, A. T. (1967). Single-channel operation in the brain. *Acta Psychologica, 27*, 5–22. doi: 10.1016/0001-6918(67)90040-6

Westermann, R., Spies, K., Stahl, G., & Hesse, F. W. (1996). Relative effectiveness and validity of mood induction procedures: A meta-analysis. *European Journal of Social Psychology, 26*, 557–580. doi: 10.1002/(sici)1099-0992(199607)26:4<557::aid-ejsp769>3.0.co;2-4

Whitney, P., Rinehart, C. A., & Hinson, J. M. (2008). Framing effects under cognitive load: The role of working memory in risky decisions. *Psychonomic Bulletin and Review, 15*, 1179–1184. doi: 10.3758/pbr.15.6.1179

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. *Human Factors, 25*, 227–248. doi: 10.1177/001872088302500209

Wilbertz, G., Tebartz van Elst, L., Delgado, M. R., Maier, S., Feige, B., Philipsen, A., & Blechert, J. (2012). Orbitofrontal reward sensitivity and impulsivity in adult attention deficit hyperactivity disorder. *NeuroImage, 60*, 353–361. doi: 10.1016/j.neuroimage.2011.12.011

Williams, G. V., & Castner, S. A. (2006). Under the curve: Critical issues for elucidating D1 receptor function in working memory. *Neuroscience, 139*, 263–276. doi: 10.1016/j.neuroscience.2005.09.028

Worsley, K. J., & Friston, K. J. (1995). Analysis of fMRI time-series revisited – again. *NeuroImage, 2*, 173–181. doi: 10.1006/nimg.1995.1023

Wrede, K. H., Johst, S., Dammann, P., Umutlu, L., Schlamann, M. U., Sandalcioglu, I. E., . . . Maderwald, S. (2012). Caudal image contrast inversion in MPRAGE at 7 Tesla: Problem and solution. *Academic Radiology, 19*, 172–178. doi: 10.1016/j.acra.2011.10.004

Wu, T., Liu, J., Hallett, M., Zheng, Z., & Chan, P. (2013). Cerebellum and integration of neural networks in dual-task processing. *NeuroImage, 65*, 466–475. doi: 10.1016/j.neuroimage.2012.10.004

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003). Task switching: A high-density electrical mapping study. *NeuroImage, 20*, 2322–2342. doi: 10.1016/j.neuroimage.2003.08.010

Yarkoni, T., Braver, T. S., Gray, J. R., & Green, L. (2005). Prefrontal brain activity predicts temporally extended decision-making behavior. *Journal of the Experimental Analysis of Behavior, 84*, 537–554. doi: 10.1901/jeab.2005.121-04

Yildiz, A., Chmielewski, W., & Beste, C. (2013). Dual-task performance is differentially modulated by rewards and punishments. *Behavioural Brain Research, 250*, 304–307. doi: 10.1016/j.bbr.2013.05.010

Yuen, K. S. L., & Lee, T. M. C. (2003). Could mood state affect risk-taking decisions? *Journal of Affective Disorders, 75*, 11–18. doi: 10.1016/S0165-0327(02)00022-8

Zamarian, L., Sinz, H., Bonatti, E., Gamboz, N., & Delazer, M. (2008). Normal aging affects decisions under ambiguity, but not decisions under risk. *Neuropsychology, 22*, 645–657. doi: 10.1016/j.neuropsychologia.2006.11.012

Zamarian, L., Weiss, E. M., & Delazer, M. (2010). The impact of mild cognitive impairment on decision making in two gambling tasks. *Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 66B*, 23–31. doi: 10.1093/geronb/gbq067

Zillmann, D. (1978). Attribution and misattribution of excitatory reactions. In J. H. Harvey, W. J. Ickes & R. F. Kidd (Eds.), *New directions in attribution research* (Vol. 2, pp. 335-368). Hillsdale, NJ: Erlbaum.

Zimmermann, P., & Fimm, B. (2002). *Testbatterie zur Aufmerksamkeitsprüfung (TAP), Version 1.7 [Test for attentional performance, version 1.7]*. Herzogenrath, Germany: PSYTEST Psychologische Testsysteme.

Zuckerman, M. (1979). *Sensation seeking: Beyond the optimal level of arousal.* Hillsdale, NJ: Erlbaum.