AN AFFECTED MIND

- On the relevance of additional demands, task difficulty and the process of aging -

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...for my family

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Abstract

The complexity of our daily life constantly increases. As a result, we are performing two or even more tasks simultaneously, we deal with complex demands and we make decisions in situations that are highly influenced by additional stimuli. At the same time, our society is rapidly aging and thus problems in handling these situations become more and more apparent.

Therefore, the thesis at hand considers the influence of additional demands, task difficulty and the process of aging on cognitive task performance on a behavioral but also neurophysiological level. The three experiments comprised in the present thesis systematically investigate the performance of a broad variety of cognitive tasks from simple reaction time tasks to dichotomous choice and double inhibition tasks with additional mnemonic components, but also a more applied gambling task while simultaneously performing different motor demands. The neurophysiological results highlight a facilitating effect of additionally performed motor demands. Regarding the behavioral findings, significant effects of the additional motor demands were identified only in the most complex cognitive task - the gambling task of the third experiment. Here, participants showed a more disadvantageous behavior with increasing motor demands. Considering the influence of cognitive task difficulty, the second experiment impressively highlights a linear increase in response time with increasing cognitive task difficulty / complexity. Furthermore, age-related differences in cognitive task performance were identified under both single- and dual-task conditions.

The present results are discussed in the context of information processing, executive functions, decision making and attention but also with regard to the process of aging. Based on the findings at hand, the increasing complexity of our daily life and thus the numerous aspects that affect our mind positively but also negatively, further studies should consider the present topics in a more applied context.

1. Introduction

Today, we sit in bars with friends and drink a glass of wine but at the same time, we write emails, we call our partner, we surf on Facebook, we send pictures on WhatsApp or we post messages on twitter. This situation represents only one - out of numerous daily situations - in which we are simultaneously confronted with multiple demands. Based on technical innovations, social pressure but also our own expectations, the complexity of our daily life constantly increases. Although we are able to successfully decode complex images in 100 ms (Rousselet, Thorpe, & Fabre-Thorpe, 2004), and store upwards of 10^9 bits of information over our lifetime (Von Neumann, 1958) - which is more than 50,000 times the text contained in the US Library of Congress - processing multiple demands is severely capacity limited and adversely affected by numerous variables such as task difficulty or the process of aging. To get a better understanding of humans' ability of handling these situations, as well as the associated interferences, numerous previous studies out of the field of dual-task investigated both cerebral processes (e.g. Herath, Klingberg, Young, Amunts, & Roland, 2001; Jiang, 2004; Schubert & Szameitat, 2003; Sigman & Dehaene, 2008; Szameitat, Schubert, Müller, & Von Cramon, 2002) as well as humans' behavior (e.g. Karatekin, Couperus, & Marcus, 2004; Sala, Baddeley, Papagno, & Spinnler, 1995), since over 100 years (e.g. Solomon & Stein, 1896). Here, within standardized experiments, two assumed competitive tasks are presented and selected parameters (e.g. response-time, neural activity) are used to quantify the effect of simultaneously performing two or even more tasks, compared to single-task requirements or other dual-task situations.

Within the present work, dual-task demands are systematically increased by primary and secondary task-difficulty. In this context, simple reaction tasks, basal but also more applied decision tasks are presented while participants are faced with additional motor demands. The first experiment combines basal decision tasks with different motor conditions. Using electrophysiological methods, this experiment primarily focus on the underlying mechanisms. The second experiment investigates the effect of cognitive task difficulty from simple reaction tasks to dichotomous choice and double inhibition tasks with additional mnemonic component from a behavioral point of view. Furthermore, the study aims to investigate the effects of additional motor demands as well as the process of aging. In contrast to the first two studies - which comprise very basal decision-making tasks - the third experiment investigates decision making on a more applied level. Here, participants are asked to perform a gambling task under different motor demands.

As it became obvious during the first paragraph, the present thesis comprises three major topics, highly relevant in this day and age: the effects of additional demands, task difficulty / complexity and the process of aging. Along with the relevance of task difficulty / complexity and additional demands, the necessity of investigating age-related differences is frequently discussed in scientific, political but also social contexts. Considering the proportion of older adults - over the age of 65 years - of the entire population of Germany, the number increased from 15% in 1991, to 21.1% in 2015 and is constantly growing (Statista, 2017). In this context, the increasing complexity of daily situations again plays a highly relevant role. While previous age-related studies pointed out the problem of talking while walking and thus the increasing risk of falling in the elderly (Lundin-Olsson, Nyberg, & Gustafson, 1997; Verghese et al., 2007), demands of everyday life - with wich older people had to deal with - are much higher. Here, a simple trip to the next capital state requires the ability of handling computational systems and technical innovations while simultaneously concentrate on the traffic (while driving a car) or keep the balance (while standing in the railway).

Based on its relevance as well as previous findings, the present thesis address the following hypothesis, respectively:

- Additional demands as well as increasing task difficulty are reflected in differences of the event-related potentials P2/200 & P3/300.
- Additional demands as well as increased task difficulty lead to a reduction in cognitive task performance.
- Dual-task cost increases during the process of aging.

Before new evidence will be provided - across the three studies comprised in this thesis - previous findings as well as existing gaps in the research of relevant topics will be focused in detail during the theoretical background.

2. Theoretical background

The experiments comprised in the present work can be summarized under the topics of information processing, executive functions, decision making, dual-task and electroencephalography. Therefore, the present chapter of the theoretical background delves into these subjects by considering relevant models, existing theories, behavioral results as well as individual differences. Furthermore, each chapter includes previous findings of the underlying mechanisms. Although the manuscript does not focus on an imaging level, these findings were supplemented to ensure a comprehensive insight into the topics.

2.1. Information processing

We are faced by millions of bits of sensory perceptions every day. Processing this information is one of the major fields of interest in cognitive sciences. In 1958, Broadbent described a first model named ‘filter model of attention’, which aimed to provide a better understanding of humans’ information processing. The model is based on the idea that the brain retains information in a temporary sensory storage. Furthermore, the author suggested that this information, will be lost unless it is selected/filtered via attentional processes (Birnboim, 2003). While Broadbent argued for an early process of filtering, later models proposed the opposite. For example, Deutsch and Deutsch (1963) suggested that the filtering process occurred at some point in the memory search, decision and response stages, where all information is analyzed automatically not during the perception or feature extraction stage. In this context, another model was suggested by Treisman (1960). Within his experiments, participants were asked to ignore whatever they hear in one ear. The results showed an increased error rate only initially after changing the ear that should be ignored. Based on his findings, Treisman (1960, 1964) suggested that the filter has a limited capacity that could be allocated by the subject to the various input channels rather than acting as an all-or-none barrier. Furthermore, the author described information processing as being allocated to various channels and thus attenuated to degrees controlled by the subject himself (Schneider & Shiffrin, 1977, for review). Within a further paradigm introduced by Sternberg, participants had to decide whether a probe digit was included in a set of characters (typically 1-6 in number). Performing the task, participants generally showed a linear increase in reaction time to the probe digit with an increasing number of items in the memory set. Sternberg interpreted the results as a serial and exhaustive search through the memory set, which increased in time by increasing the number of items (Sternberg, 1966; Sternberg, 1975).

The most widely used model of information processing was introduced by Atkinson and Shiffrin (1968). Their ‘stage theory model’ comprises a cognitive path for transferring information from temporary to long-term memory storage (see also Figure 1). Furthermore, the authors proposed a division of human memory and information processing into 1) labile control processes and 2) learned or inherent structural components.

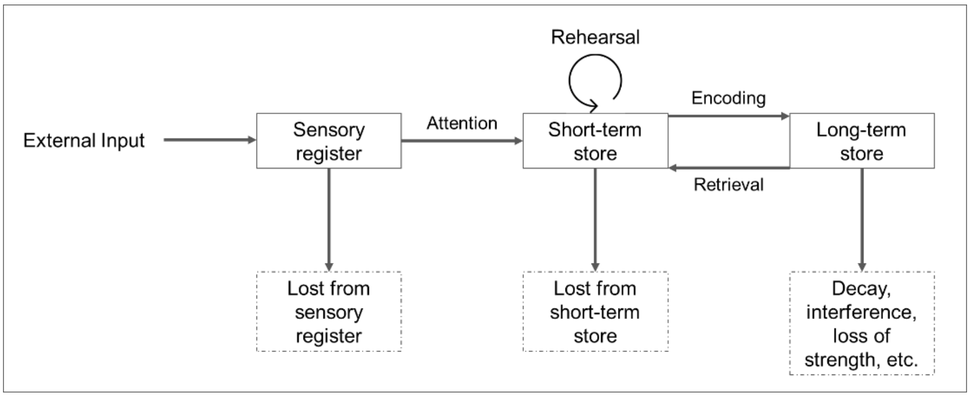


Figure 1 Stage theory model according to Atkinson & Shiffrin (1968).

The first stage - named sensory register - is described as being temporally limited to several hundred milliseconds and divided into separate sections for each type of sensual perception. Each section transfers perceptions to a general short-term store, rather than a specific short-term store (see also Lutz & Huitt, 2003). Although the authors argue that there is no possibility to transfer information directly into the long-term store, it is additionally assumed that the process of transfer information into the short-term store is accompanied with scanning related information in the long-term memory and feeding it into the short-term store. In order to transfer information successfully into the short-term store, attention and automaticity play a major role. Short-term store as a second stage is also temporally limited. Along with receiving and holding input from the sensory register, this stage of information processing retrieves information from and encodes it into long-term memory. Therefore, the short-term store can be seen as a mediator between the sensory register and long-term store. In order to avoid a loss of information, the process of rehearsal becomes highly relevant. Considering the capacity of short-term memory, previous studies suggested the temporal limitation within 15-30 seconds for unrehearsed information as long as no other action is taken simultaneously (Lutz & Huitt, 2003; for review). As part of the memory system, the amount and form of information transferred into long-term store must be seen as a function of controlled processes (Atkinson & Shiffrin, 1968). Furthermore, the authors assume that the transfer itself is an unvarying feature of the system, which takes place even when the subjects are not trying to store material in long-term memory.

Along with the ‘stage theory model’, further evidence for explaining information processing in humans, is provided by numerous other models. For example, the ‘levels of processing’ model (Craik & Lockhart, 1972) must be seen as one of the first alternatives to Atkinson and Shiffrin’s model. Within their articles, the authors postulated that the kind and the amount of elaboration are highly relevant for remembering information. Another theory was introduced by Paivio (Clark & Paivio, 1991; Paivio, 1971; Paivio, 1986). Within his ‘dual coding theory’, the author suggested two distinct subsystems of cognition, namely a verbal and a non-verbal (imagery) system that work independently or cooperatively. In contrast to previous models, the ‘schema theory’ (Rumelhart, 1980) is based on the idea of multiple locations of information storage. Furthermore, the theory explains how information is structured and how this structure influences incoming information.

In addition to theoretical models of information processing neurophysiological findings provide evidence of changes in the activation pattern of underlying structures and the alpha rhythm (e.g. Klimesch, 1999), as well as the event-related brain potential P3/300 (e.g. Strayer & Kramer, 1990; Strayer, Wickens, & Braune, 1987). For example, Jiang and He (2006) measured brain activity while participants viewed neutral, fearful and scrambled faces, either visible or rendered invisible through inter-ocular suppression. Among others, the results showed activity in the right fusiform face area, the right superior temporal sulcus and the amygdala to visible faces. In the invisible conditions, activity in the right fusiform face area to both neutral and fearful faces was reduced, whereas the activity in the right superior temporal sulcus was robust to invisible fearful faces but not to neutral faces. Furthermore, highly interesting findings come from split-brain experiments. Here, it is demonstrated that the left hemisphere is more involved in processing verbal/analytic material, whereas the right hemisphere is more involved in processing visuo- spatial/synthetic material (Sperry, 1982). While the field of electroencephalography will be focused in detail within a later chapter, the two studies conducted by Strayer (Strayer & Kramer, 1990; Strayer et al., 1987) should be mentioned in the present context. Within the first study, Strayer et al. (1987) examined the effects of aging on information processing. Using the Sternberg memory search task, participants showed an increased P3/300 latency with increasing set size, as well as differences between positive and negative stimuli. Furthermore, the authors found a monotonic and marginally significant increase in latency from the youngest to the oldest group. Regarding the amplitude, there was a slight but non-significant age-related decline at the parietal electrode, whereas the frontal electrode site revealed a monotonic increase in P3/300 amplitude from younger to older adults. Within the second study, Strayer and Kramer (1990) investigated the attentional demand of automatic and controlled processing. While the authors used the Sternberg task again, they paired it with a running memory task. Based on their results, Strayer and Kramer proposed the P3/300 as reflecting the obligatory allocation of attention to task-relevant events during automatic processing. Here, the authors once again demonstrated the necessity of attention and automaticity within information processing.

2.1.1. Capacity limitations in information processing

Despite the impressive complexity and processing power of the human brain, it is generally accepted that our brain cannot process every information with which it is confronted. This becomes apparent, not only in complex tasks like talking on a mobile phone while driving a car (e.g. Strayer & Drews, 2007), but also in simple tasks like selecting motor responses for two distinct sensory events (Dux, Ivanoff, Asplund, & Marois, 2006). Based on the theories stated above, these limitations can occur at different levels of information processing. Furthermore, some researchers suggested the existence of different types of control systems (e.g. Atkinson, & Shiffrin, 1971). One of the most significant work in the context of capacity limitations was conducted by Miller (1956). Within his work, the author introduced the ‘magical’ number seven (plus or minus two) as the number of bits or distinct information units that one can simultaneously track. Furthermore, Kilgard and Merzenich (1998) proposed that most neurons response maximally to repeated stimuli presented at 7-12 pulses per second. Based on their results, the authors highlighted the repetition rate transfer function as one method for describing the response capacity of cortical neurons to successive inputs. While only a few neuroimaging studies focus on capacity limitations in information processing, further evidence comes from dual-task studies highlighting the lateral frontal, prefrontal, dorsal premotor, anterior cingulate, and intra-parietal cortex as putative neural substrates for occuring interferences (e.g. Herath et al., 2001; Ivry, Franz, Kingstone, & Johnston, 1998; Jiang, 2004; Jiang, Saxe, & Kanwisher, 2004; Luck, 1998; Marois, Larson, Chung, & Shima, 2006; Osman & Moore, 1993; Pashler, 1994; Szameitat et al., 2002). Here, it is largely accepted that occurring interferences in simultaneously performing two or even more tasks are based on a limited capacity for task-processing, which will be discussed in further detail in the dual-task chapter.

2.1.2. Automatic versus controlled information processing

Automatic processing is the result of extensive training on exactly the same task and not limited by short-term memory capacity. Furthermore, it is characterized as faster and allows the parallel processing of two or even more requirements. Controlled processes as the counterpart are described as tightly capacity limited but balanced by the benefits derived from the ease with which they may be set up, altered and applied in novel situations for which automatic sequences have never been learned. Therefore, controlled processes are described as slow, serial and associated with a high amount of attention (Fisk & Schneider, 1983; Schneider & Fisk, 1982; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

According to the works conducted by the group of Schneider and Shiffrin, training enables the change of cognitive task execution. For example, Schneider, Domais and Shiffrin (1984) suggested that a novice reader needs a few seconds to decode each letter and reports a high error rate, whereas a competent reader can simultaneously decode 25 letters per second and consciously access the meaning of the word. Within their article, the authors introduced the idea of a four-stage process of transformation, from fully controlled to fully automatic processing. Furthermore, Schneider et al. (1984) proprosed that the assignment of processes to either automatic or controlled must be seen as oversimplified. Another theory in this context was stated by Logan (1988). In accordance with Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977), the author suggested that the degree of automaticity rather than resource limitations moderates the effects of attention in information processing. While the aspect of attention will be considered in further detail in the next sub-chapter, the present sub-chapter will be completed with a brief look at neuropsychological as well as neurophysiological findings. For example, *neuropsychological* studies provide evidence of a differentiation between automatic and controlled processing by focusing on different populations such as brain lesions (Knight, 1991; Sirigu, Zalla, Pillon, Grafman, Agid, & Dubois, 1995a; Sirigu, Zalla, Pillon, Grafman, Dubois, & Agid, 1995b), frontal lobe damage (e.g. Shallice & Burgess; 1991), Aphasia (e.g. Milberg, Blumstein, Katz, Gershber, & Brown, 1995), Amnesia (e.g. Jacoby, 1991), Alzheimer’s disease (e.g. Abbenhuis, Raaijmakers, Raaujmakers, & Van Woerden, 1990; Chenery, Ingram, & Murdoch, 1994), Parkinson’s disease (e.g. Henik, Singh, Beckley, & Rafal, 1993; Revonsuo, Portin, Koivikko, Rinne, & Rinne, 1993), and Multiple Sclerosis (e.g. Kujala, Portin, Revonsuo, & Ruutiainen, 1994) (Birnboim, 2003, for review). These findings are supplemented by *neurophysiological* findings reporting increased activity in the prefrontal and anterior cingulate cortex during the performance of novel, more difficult tasks (associated with controlled processing) compared to overlearned tasks (associated with automatic processing) (e.g. Birnboim, 2003; Büchel, Coull, & Friston, 1999; Frith, Friston, Liddle, & Frackowiak, 1991; Jansma, Ramsey, De Zwart, Van Gelderen, & Duyn, 2007; Raichle et al., 1994).

2.1.3. Attention and awareness in information processing

Two aspects that need to be considered in the context of information processing are attention and awareness. Attention can selectively act at multiple stages of information processing and is - among other contributors - responsible for occurring limitations in information processing (Kahneman, 1973). For example, Schneider and Shiffrin (1977) described selective attention as being responsible for the fact that a sensory input can perceived or remembered better in one compared to another. In this context, Brisson and Jolicoeur (2007) showed that the performance of one discrete task can delay attention capture by other stimuli for several hundred milliseconds. Focusing on visual information processing, Müller, Gruber and Keil (2000) reported an increased spectral power in the electroencephalogram when subjects attended a certain stimulus compared to ignoring the stimulus. Furthermore, they revealed a shift in spectral gamma band power to the contralateral hemisphere related to the shift in subjects' attention to one visual hemifield.

2.1.4. Age-related differences in information processing

Different people will process the same information in different ways. Investigating this hypothesis, Riding, Glass, Buttler and Pleydell-Pearce (1997) provided evidence of various individual cognitive styles by using electroencephalography while participants had to identify target words among a varied number of non-target words. In the past, numerous aspects such as genetic traits (e.g. Flavell, Miller, & Miller, 2002), gender (e.g. Darley & Smith, 1995), age (e.g. Bryan & Luszcz, 1996) and intelligence (e.g. Sheppard & Vernon, 2008), but also neurological disorders, including brain injury (e.g. Zahn & Mirsky, 1999), multiple sclerosis (e.g. Archibald & Fisk, 2000;) and symptomatic HIV (Llorente et al., 1998) are frequently studied in the context of information processing. Thereby, the effect of aging is one of the most investigated aspects that has been examined for more than 100 years in this context (e.g. Galton, 1883). For example, Nettelbeck & Rabbitt (1992) highlighted the mediating role of information processing speed within the relationship of age and cognitive performance. 104 subjects ranging from 54 to 85 years performed four-choice-reaction time tasks, an inspection time and scores on a speed coding-substitution task. While the authors indicated an age-related decrease in free-recall performance by 22%, Bryan and Luszcz (1996) concluded that task-independent speed of information procession appears to mediate the relationship between age and free-recall performance. The role of information processing speed was also highlighted by Salthouse (Salthouse, 1991; Salthouse, Fristoe, & Rhee, 1996) and Verhaeghen and Salthouse (1997). The authors suggested that the speed of information processing mediates much of the age-related decline in working memory, fluid intelligence, spatial visualization and episodic memory. Furthermore, Salthouse and Ferrer-Caja (2003) and Finkel, Reynolds, McArdle and Pedersen (2007) demonstrated the relevance of age-related declining information processing speed as an important variable that predates a decline of general cognitive functions (Salthouse & Ferrer-Caja, 2003; Finkel et al., 2007). Focusing on age-related differences in verbal fluency, previous studies have reported indifferent findings. While clear evidence of an age-related decline in verbal fluency comes from Bryan, Luszcz and Crawford (1997) and Hultsch, Hertzog, Small, McDonald-Miszczak and Dixon (1992) found no evidence of an age-related decline in verbal fluency. Furthermore, Lindenberger, Mayr, & Kliegl (1993) and Salthouse (1993) revealed moderate negative correlations between age and fluency performance.

Regarding the type of stimuli, Hale, Myerson, Faust and Fristoe (1995) reported a reduced age-related decline in tasks, involving lexical information compared to non-lexical information tasks. In the use of arithmetic tasks, findings vary according to the type of task. For example, paper-and-pencil tests revealed small to non-existent age differences (e.g. Geary, Salthouse, Chen, & Fan, 1996; Geary & Wiley, 1991; Schaie, 1996), whereas reaction time tasks indicated a deterioration with increasing age (e.g. Allen, Smith, Jerge, & Vires-Collins, 1997; Salthouse & Coon, 1994; Siegler & Lemaire, 1997). Considering the effect of non-target stimuli, it is shown that an increasing number of non-target stimuli leads to increasing interferences in both, letters and digits (Barber, 1981; Duncan, 1980). Regarding age-related effects, no differences in non-targets were reported when the target occupied a single, fixed position in a display (Farkas & Hoyer, 1980; Madden, 1983; Wright & Elias, 1979). Furthermore, varying the position of the stimuli as well as presenting confusable targets and non-targets, Farkas and Hoyer (1980) showed a decrease in speed of performance with increasing age. Investigating the role of stimulus size, Stark and Coslett (1993) identified faster responses to small letters in older participants, whereas younger participants responded equal with global and local letters. While Stark and Coslett (1993) aimed at investigating age-related differences in the 'Navon effect', a more recent study conducted by Roux and Ceccaldi (2001) used a selective-attention task. Within their experiment, the authors reported greater global interferences on local identification in older compared to younger participants, but equal effects of attentional shifts on reaction time.

Based on these findings, the question emerges whether age-related deficits in information processing can be ascribed to changes in anatomical and/or physiological processes. Here, Greenwood (2007) and Greenwood and Parasuraman (2010) provided evidence of both. A significant association between white matter integrity and a general factor of information processing speed for anisotropy and diffusivity, but not with general intelligence or memory were shown by Penke et al. (2010). Furthermore, Madden, Bennett and Song (2009) reported a relation between white matter integrity and the effects on perceptual speed. In agreement with O'Sullivan, Jones, Summers, Morris, Williams and Markus (2001), Madden et al. (2009) proposed that white matter integrity and speed of information processing are especially prone to aging effects, and thus age-related cognitive decline may occur as a result of cortical disconnection, which is related to white matter pathways (see also Penke et al., 2010).

In the present chapter, I have provided an overview of different models of information processing. Here, the ideas of filtering information (Broadbent, 1958), the limited capacity (Treisman, 1960, 1964) and the different stages (Atkinson & Shiffrin, 1968) or levels (Craik & Lockhart, 1972) of information processing were highlighted. The models were supplemented by more recent neurophysiological findings. Regarding the localization, a brief overview of split brain experiments demonstrated different hemispheric activity regarding the type of stimulus. Along with the location, Strayer and Kramer reported differences in latency and amplitude of event-related potentials, regarding the type of stimulus. The chapter of capacity limitations in information processing highlighted the ‘magical number seven’ introduced by Miller (1956), as well as the maximal capacity of most neurons to respond to repeated stimuli at 7-12 pulses per seconds (Kilgard & Merzenich, 1998), respectively. While automatic and controlled processes were defined in the context of information processing, in the subsequent chapter the early statement of Logan (1988) should be highlighted again. Within his article, the author reported that the degree of automaticity rather than resource limitations moderates the effects of attention in information processing. The aspect of attention as well as awareness has been focused in a further sub-chapter. Here, the statement of Kahneman (1973) should be pointed out respectively. The author described that attention can selectively act at multiple stages of information processing and must be seen as being responsible for occurring limitations. Completing this chapter with age-related aspects, the last sub-chapter described a decline in information processing speed with increasing age as an important variable that predates a decline of general cognitive functions. Furthermore, the relevance of stimulus type, the way of presentation, and the stimulus size have been highlighted as dependent variables influencing information processing during the process of aging.

2.2. Executive functions

Choosing the examples of hitting a baseball and operating a motor vehicle, Brown, Collier and Night (2013) described the relevance of coordinating and integrating perceptual, motor and decision-making processes in daily situations. Along with its relevance, these processes are directly linked to higher cognitive functions, called executive functions. These functions are generally conceptualized as cognitive processes, responsible for monitoring, regulating and coordinating the execution of goal-directed behavior (Alvarez & Emory, 2006; Baddeley & Hitch, 1974; Balota, Law, & Zevin, 2000; Braver, Gray, & Burgess, 2007; Diamond, 2006; Engle & Kane, 2004; Hasher & Zacks, 1988; Jacoby, Bishara, Hessels, & Toth, 2005; Logan, 2003; Miller & Cohen, 2001; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; Posner & DiGirolamo, 1998; Royall & Mahurin, 1996; Shallice & Burgess, 1993; Stuss & Alexander, 2000; Zelazo & Müller, 2002), but the underlying construct and its definition remains complex and unclear. This becomes obvious in the diversity of terms used for designating executive functions (Dores, Carvalho, Barbosa, Martins, De Sousa, & Castro-Caldas, 2014; Pennington, 1997; Salthouse et al., 2003; Stuss & Benson, 1984; Stuss & Benson, 1986). Although there is no general agreement on how to best define or conceptualize executive functions, they are considered as key mechanisms in many models of normal and abnormal cognition, such as cognitive development (e.g. Lyon & Krasnegor, 1996; Zelazo, Carter, Reznick, & Frye, 1997), age-related decline in cognitive abilities (e.g. Hasher, Zacks, & May, 1999; Lowe & Rabbitt, 1997), and disorders such as attention-deficit/hyperactivity disorder (Barkley, 1997), autism (Russell, 1997), Schizophrenia (Frith, 1992) and substance use problems (Garavan & Stout, 2005). While executive functions play a central role in neuropsychological theories of behavior control (Ferrier, 1886; Luria, 1973; Stuss & Knight, 2002), early findings describe these processes in the way of hierarchical models of the brain (e.g. Luria 1970; MacLean, 1955), as well as a central integrative factor and abstraction (Halstead, 1948; Pikas, 1966). A more recent approach was developed by Zelazo et al. (1997) but influenced by Luria’s idea of an interactive functional system (Luria, 1973). The authors conceptualized executive functions as a complex function - or macrostructure - including executive sub-functions that work together to accomplish higher-order functions of solving problems. Considering theories of cognitive control, authors typically include an executive component responsible for directing thoughts and coordinating goal-directed behavior (Baddeley & Hitch, 1974; Balota et al., 2000; Banich, 2009; Braver et al., 2007; Brown, Johnson, Sohl, & Dumas, 2015; Engle & Kane, 2004; Hasher & Zacks, 1988; Jacoby et al., 2005; Logan, 2003; Miyake et al., 2000; Phillips, 1997; Posner & DiGirolamo, 1998; Royall & Mahurin, 1996; Shallice & Burgess, 1993). Focusing on the components of executive functions, Packwood, Hodgetts and Tremblay (2011) reviewed 60 of the most frequently cited articles and identified 68 different functions summarized under the umbrella term of executive functions. These higher-order mental operations involve planning, judgment, decision making, suppression of irrelevant information, monitoring and control of behavior, resisting distractions, reasoning, working memory, dual-tasking, inhibition of prepotent responses, self-regulation, sequencing of behavior, planning, flexibility, shifting or switching and control of attention, among others, as well as the regulation of other cognitive processes, such as language, perception and memory (e.g. Baddeley, 1996; Banich, 2009; Brown et al., 2013; Eslinger, 1996; Fournier, Larigauderie, & Gaonac'h, 2004; Fuster, 2000; Jurado & Rosselli, 2007; Koechlin & Summerfield, 2007; Logan, 1985; Miyake et al., 2000; Shimamura, 2000; Strauss, Sherman, & Spreen, 2006; Stuss & Alexander, 2000; Stuss & Benson, 1986; Waltz et al., 1999). Furthermore, Brown et al. (2013) described the processes of coordination, sequencing and integration, as well as scheduling plans and actions as involved in executive functions. Additionally, some investigators suggested that performing complex locomotor tasks such as gait is strongly related with executive functions (Ble et al., 2005; Cocchini, Della Sala, Logie, Pagani, Sac7co, & Spinnler, 2004; Hausdorff, Yogev, Springer, Simon, & Giladi, 2005; Persad et al., 1995; Sheridan, Solomont, Kowall, & Hausdorff, 2003; Springer, Giladi, Peretz, Yogev, Simon, & Hausdorff, 2006). In a more general way, Lezak (1982, 1987) described the components of executive functions as the skills to formulate goals, plan strategies and self-evaluate one's behavior. Furthermore, executive functions are discussed as conscious and controlled processes that guide thoughts and actions (Baddeley, 1992; Logan, 1985; Norman & Shallice, 1986; Phillips, 1997). Furthermore, Elliott (2003) summarized the components of executive functions as a set of cognitive processes, encompassing a wide variety of controlled abilities. Based on previous findings, Bouazzaoui, Angel, Fay, Taconnat, Charlotte and Isingrini (2014) came up with the idea that these components could be viewed as supporting the generation of memory strategy processes, such as focusing and maintaining attention on abstract representations (Bouazzaoui et al., 2010; Bryan, Luszcz, & Pointer, 1999; Moscovitch & Winocur, 1992; Shimamura, 1995; Taconnat et al., 2006; Taconnat, Clarys, Vanneste, Bouazzaoui, & Isingrini, 2007; Taconnat et al., 2009). Summarizing the underlying processes to formulate higher-order components, Lezak (1995), Spreen and Strauss (1998) as well as Jurado and Rosselli (2007) introduced four components of executive functions. While Lezak (1995) and Spreen and Strauss (1998) highlighted the functions of volition, planning, purposive action and effective performance, Jurado and Rosselli (2007) reported goal formation, planning, carrying out goal-directed plans and effective performance as the four major components. By contrast, the most commonly used and replicated factor model of the executive system referenced response inhibition (inhibition), working memory and set-shifting (shifting) (Jurado & Rosselli, 2007; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Logan, 1985; Miyake et al., 2000). While other components such as dual-tasking (e.g. Logie, Cocchini, Delia Sala,

& Baddeley, 2004; Salthouse, Atkinson, & Berish, 2003) and resisting proactive interference (Friedman & Miyake, 2004) have also been addressed, the three components of inhibition, working memory and shifting have dominated recent executive function research. Using structural equation modeling, Miyake et al. (2000) - for example - postulated that executive functions are best characterized as comprising the three following processes:

- Inhibition, as a basic executive control process that includes suppressing dominant, automatic responses and resisting distractions.
- Working memory, entails keeping track of old and new information, replacing appropriate information that is no longer current or relevant with newer, updated information.
- Shifting, which involves shifting attention back and forth between multiple tasks or cognitive operations.

A similar notion was highlighted in an impressive article by Packwood et al. (2011). Within a multi-perspective approach to the conceptualization of executive functions, the authors created a model based on existing executive function literature that summarized the aspects of executive functions under the main terms of inhibition, set-shifting, working memory, planning, and fluency. Regarding the aims of the present work, the following chapter highlights the three executive functions described by Miyake et al. (2000).

2.2.1. Inhibition

Inhibition is described as the ability that enables us to overcome automatic and experienced behavior by controlling one’s attention, behavior, thoughts, and emotions (Diamond, 2013; Shallice & Burgess, 1993). Deficits in this function are frequently described in clinical contexts such as attention deficits / hyperactivity disorder (Barkley, 1997, Sergeant, Geurts, & Oosterlaan, 2002), Tourette syndrome (Peterson et al., 1998), obsessive-compulsive disorder (Enright & Beech, 1993), or disinhibition syndrome (Shulman, 1997).

At present, the go-/nogo task is the most frequently used paradigm for quantifying inhibition (Donders,1969). Within the task, participants had to react to a certain stimulus (e.g. letters) and inhibit to another stimulus (e.g. numbers). In the past, the go-/nogo task was used in numerous different settings. In visual paradigms, researchers used pictures, objects, letters, numbers, etc. (Thorpe, Fize, & Marlot, 1996), whereas auditory paradigms comprised single tones, voices, noises etc. (e.g. Miller, Franz, & Ulrich, 1999). Furthermore, the paradigm has been used in behavioral (Verbruggen & Logan, 2008), electrophysiological (Bokura, Yamaguchi & Kobayashi, 2001), as well as imaging studies (e.g. Simmonds, Pekar, & Mostofsky, 2008). After completing five experiments of the go-/nogo task, Verbruggen and Logan (2008) proposed that automatic and controlled inhibition can work together to guide goal-directed behavior. Within electrophysiological studies, the go-/nogo task is a famous paradigm used for investigating event-related potentials, especially the P3/300 (e.g. Eimer, 1993; Enriquez-Geppert, Konrad, Pantev, & Huster, 2010; Jodo & Inoue, 1990). Therefore, within the chapter of Electroencephalography, I will return to this point by focusing on the cited studies in more detail. Considering the activated structures in performing inhibition tasks, early non-human studies highlighted the relevance of the dorsolateral prefrontal cortex (Butters, Butter, Rosen, & Stein, 1973; Iversen & Mishkin, 1970; Sasaki, Gemba, & Tsujimoto, 1989). Further evidence comes from human studies, demonstrating a network comprising the supplementary motor area (Humberstone et al., 1997; Kawashima et al., 1996), dorsal and ventral frontal regions (Casey et al., 1997a; Kawashima et al., 1996; Konishi, Nakajima, Uchida, Sekihara, & Miyashita, 1998; Tsujimoto, Ogawa, Nishikawa, Tsukada, Kakiuchi, & Sasaki, 1997), the cingulate cortex (Casey et al., 1997b) as well as the occipital and parietal lobe (Butters et al., 1973; Casey et al., 1997b; Humberstone et al., 1997) associated with response inhibition (see Simmonds et al., 2008 for a review). The role of dorso-lateral prefrontal cortex as a common mechanism in inhibition was investigated by Konishi, Nakjima, Uchida, Kikyo, Kameyama and Miyashita (1999). Six healthy people aged 20-31 performed a go-/nogo task as well as the ‘Wisconsin Card Sorting Test’ while being scanned in a functional magnetic resonance imaging. The results confirmed the involvement of the posterior part of the right inferior frontal sulcus in response inhibition. The relevance of right hemispheric dominance was highlighted by Garavan, Ross and Stein (1999) and Konishi et al. (1999). Along with the right hemispheric dominance, the authors reported correlations between ventral / doral areas and the function of inhibition. Furthermore, highest prefrontal activity was found in the middle and inferior frontal gyri. A further study conducted by Garavan, Ross Murphy, Roche and Stein (2002) investigated ten female subjects (mean age 30, range 19-45 years) with the go-/ no go task and additional functional magnetic resonance imaging as well as electroencephalography. The authors reported an increased activity in the right prefrontal and parietal cortex associated with stimulus inhibition. An additional activity in cingulate regions was indicated with increasing difficulty of the inhibition tasks. Furthermore, Braver, Barch, Gray, Molfese and Snyder (2001) reported inhibition-related activity in the sub-regions of the anterior cingulate cortex as well as the right prefrontal and parietal cortex by using three different tasks (go-/nogo task, oddball, two-alternative forced-choice).

Within their meta-analysis, Braver et al. (2001) indicated a similar pattern of activity in simple and complex go-/nogo tasks comprising the right dorsolateral prefrontal and inferior parietal circuits. Considering the inhibition of motor responses, De Zubicaray, Andrew, Zelaya, Williams and Dumanoir (2000) investigated eight healthy people (mean age 27 ± 3.16 years). In their study, participants were asked to respond or inhibit to 337 larger and smaller circles, which were presented within 5.6 minutes. The participants showed increased activity in the orbital and medial frontal regions while inhibiting motor responses. Further activity was revealed in the right mid-dorsolateral prefrontal cortex and regions immediately caudal to it. Additional evidence for the underlying mechanisms of motor response inhibition comes from early findings reporting impairments in patients with anterior cortical lesions (Drewe, 1975; Luria, 1966).

To provide an overview of the underlying mechanisms, reported to be involved in response inhibition, Figure 2 visualizes the structures, summarized in this sub-chapter.

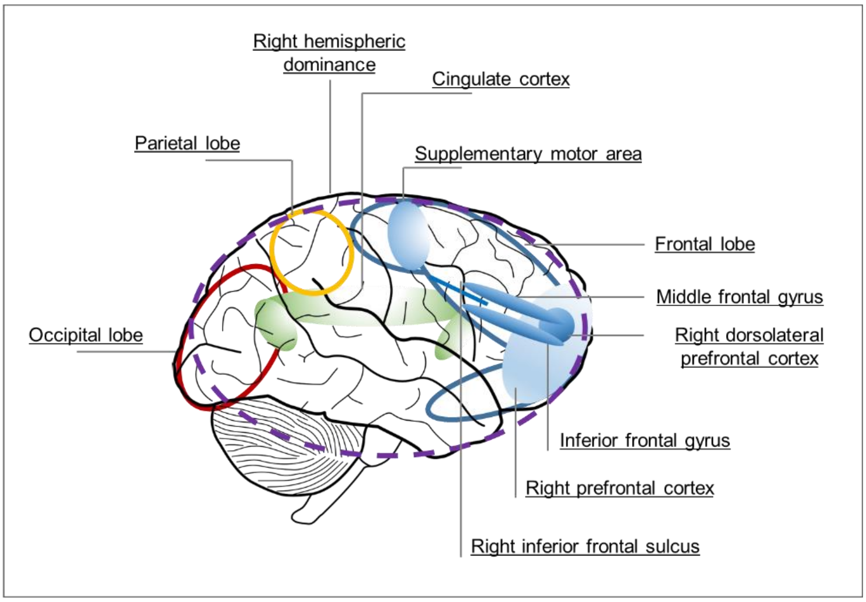


Figure 2 Underlying structures of inhibition.

In comparison of the function of inhibition and working memory, previous studies have reported similarities in activated structures (Casey et al., 1997b; Pennington, 1994; Garavan et al., 1999). Jonides, Smith, Marshuetz, Koeppe and Reuter-Lorenz (1998) for example indicated increased activity in the left prefrontal cortex within simultaneously performing a verbal working memory task and an inhibition task.

2.2.2. Working memory

Working memory can be characterized as the ‘desktop of the brain’ (Logie, 1999). Furthermore, cognitive psychologists as well as neuropsychologists describe working memory as a system responsible for maintaining and manipulating information for a short period, which is indispensable for complex tasks such as reading, understanding and arguing (Baddeley, 1992; Miyake & Shah, 1999). First described by Miller et al. (1960), Baddeley and Hitch (1974) used the term working memory to distinguish their three-component model from the previous models of short-term memory. To date, Baddeley and Hitch’s (1974) model is the most common one describing the term working memory. The original model of the authors is based on the idea of a system responsible for control attention (Baddeley & Hitch, 1974). Furthermore, it comprises a central executive that coordinates the two subsidiary storage systems, namely the phonological loop and the visuo-spatial sketchpad (Baddeley, 1998) (see also Figure 3).

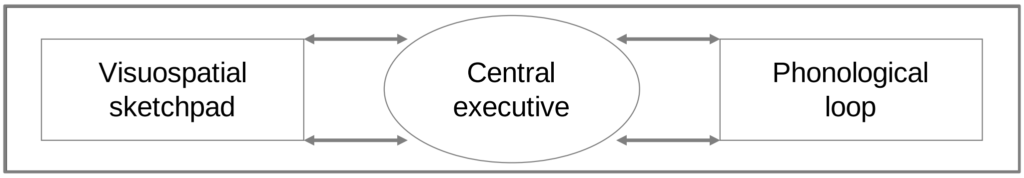


Figure 3 Baddeley & Hitch’s original model of working memory (Baddeley & Hitch, 1974).

The **central executive** is described as the ‘boss’ of the whole system, representing a superior control system, albeit which does not store any information by itself (Baddeley, 2003). Furthermore, it is responsible for controlling the execution within the working memory system and thus it is included in numerous processes such as directing attention, maintaining task goals as well as decision making and memory retrieval (McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). On the one hand, the central executive is named the most important component, while on the other hand it is the least understood component. However, various non-human (Goldman-Rakic, Cools, & Srivastava, 1996; Petrides & Baddeley, 1996) as well as human studies (Shallice, Burgess, & Robertson, 1996; Passingham, Weinberger, & Petrides, 1996) provide empirical evidence of a central executive, which is also included in other models in this context (Cowan, 1999; Engle, Tuholki, & Laughlin & Conway, 1999; Norman & Shallice, 1986; O’Reilly, Braver, & Cohen, 1999).

The **phonological loop** represents the first subsidiary system, responsible for storage and manipulation of verbal information and it plays an important role in primary speech acquisition as well as learning a second language (Cheung, 1996; Ellis, 1996). Baddeley & Hitch (1974) suggested that the phonological loop comprises two components, namely the phonological store and an articulatory rehearsal component. Furthermore, it is assumed that the content of the phonological store decays after a period of about two seconds, unless refreshed by rehearsal (Baddeley & Hitch 1974; Baddeley, 2001). In this context, the following three effects tend to appear:

- The *phonological similarity effect* describes the fact that the difficulty of storing sequences of words or letters increases with increasing similarity in its pronunciation (Conrad & Hull, 1964). This phenomenon was also reported by using unrelated letters (Conrad, 1964; Conrad & Hull, 1964) as well as unrelated words (Baddeley, 1966a). Interestingly, it becomes less relevant within the shift to long-term memory (Baddeley, 1996b). While the phenomenon also appears in high error rates of over 50%, it is assumed that alternative strategies like semantic or visual coding might play an additional role (Larsen & Baddeley, 2003; Neath, Farley, & Surprenant, 2003).
- The fact that the memory span is much worse for longer compared to shorter words is sub-sumed in the *word length effect* (Cowan & Kail, 1996) and is shown to be similarly robust as the phonological similarity effect (Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996). Increasing the word length from one to five syllables, Baddeley, Thomson and Buchman (1975) - for example - reported a direct decrease in memory span. Brown and Hulme (1995) and Neath and Nairne (1995) suggested that the difficulty of repeating longer words is based on the fact that more components had to be memorized and thus more errors can occur. Another approach describes the word length effect by the delay during the output and less by the probe itself (Cowan et al., 2003; Dosher & Ma, 1998; Lovatt & Avons, 2001). Considering the underlying mechanisms, Rypma, Prabhakaran, Desmond, Glover and Gabrieli (1999) revealed increased activity in the dorsolateral prefrontal cortex when participants had to memorize six, compared to three numbers. By contrast, Cowan et al. (2003) suggested that there are no differences in remembering shorter and longer words.
- Within the *irrelevant speech effect,* it is assumed that the presentation of concurrent or subsequent irrelevant material affects the direct repetition of the primary material (Colle, 1980; Salame & Baddeley, 1982; Jones & Macken, 1993; Neath, 2000).

The **visuo-spatial sketchpad** represents the second subsidiary system, which stores and manipulates visual and spatial information (Baddeley, 1998; Logie, 1995). Associated with non-verbal intelligence, the sketchpad must be seen as highly relevant in numerous fields, such as architecture and technology (Purcell & Gero, 1998; Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). While previous studies suggested a differentiation between visual and spatial memory (Courtney, Ungerleider, Keil, & Haxby, 1996; Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; Hecker & Mapperson, 1997; Logie & Pearson, 1997; Smith, Jonides, Koeppe, Awh, Schumacher, & Minoshima, 1995; Tresch, Sinnamon, & Seamon, 1993), others indicated a double dissociation (Haxby, Ungerleider, Horwitz, Rapoport, & Grady, 1995; Smith et al., 1995; Smith, Jonides, & Koeppe, 1996). Similar to the phonological loop, the capacity of the sketchpad is also limited. Here, Baddeley (2003) discussed the limit by three to four objects, which can be stored simultaneously, dependent on the characteristics of the components. Memorizing sentences, Logie (1986) reported that the participants remembered eight sentences with spatial linked information and six without. While the phonological loop showed a dominance in the left hemisphere, the visuo-spatial sketchpad showed greater activity in the right hemisphere (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; De Renzi & Nichelli, 1975; Hanley, Young, & Pearson, 1991).

Although the original model (Baddeley & Hitch, 1974) has already been used in numerous fields of cognitive science such as the general cognitive psychology (Hitch & Logie, 1996), computer-based modelling (Burgess & Hitch, 1992), as well as imaging studies (Smith & Jonides, 1996), in 2000 Baddeley postulated some limitations, referring to articulatory suppression and the transfer of information between codes. Based on the limitations, the author postulated two topics (Baddeley, 2000): the first addressed the kind of possible integrations of different components of working memory, all of which use different codes; and the second comprises the relationship between working memory and long-term memory. In order to take these aspects into account, Baddeley (2000) amplified the existing model by using an additional component, called the ‘episodic buffer’ (see also Figure 4).

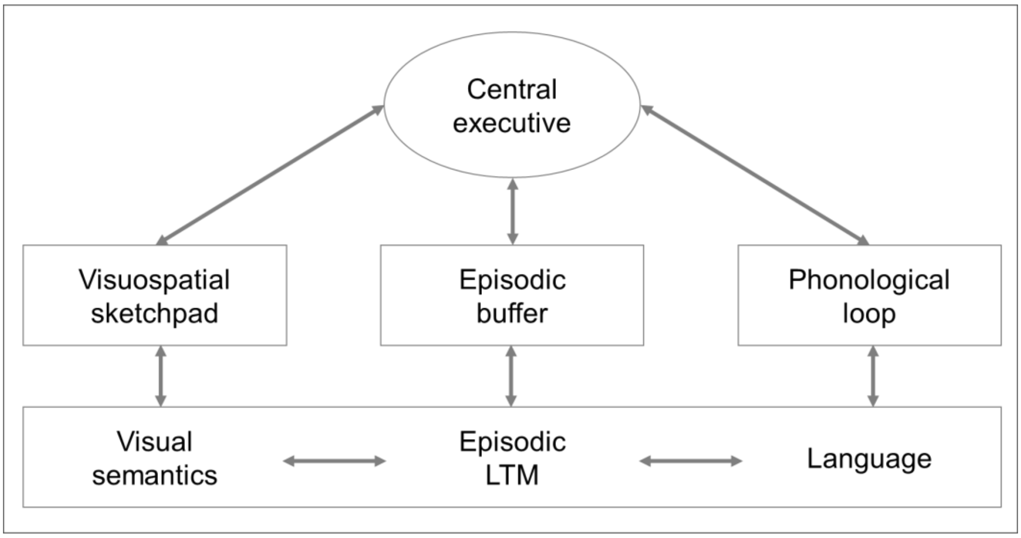


Figure 4 Amplified model of working memory (Baddeley, 2000).

The **episodic buffer** is described as temporal storage with limited capacity, capable of integrating information from different sources and controlled by the central executive (Baddeley, 2000; Baddeley, Allen, & Hitch, 2010). Furthermore, its relevance in merging multimodal information within speech processing was highlighted by Rönnberg, Rudner and Foo (2007). Similar to the episodic buffer Lehnert and Zimmer (2006) suggested a common storage for spatial representation of auditory and visual information.

Although the model conducted by Baddeley has been cited in a vast number of studies for more than 40 years, I recommend breaking away from the black-box models of the 1970s and rather creating models based on recent neuroscientific findings. Here, Constantinidis and Klingberg (2016) - for example - introduced three models of working memory: one based on non-human-primate studies, one computational model and one based on human studies. Before considering the approach of the authors in more detail, I will shed light on single previous studies, which investigating the activated structures of working memory (additionally summarized in Figure 5). One of the first studies in this context was conducted by Petrides, Alivisatos, Meyer and Evans (1993a), who reported a bilateral activity in the middle dorsolateral prefrontal and frontopolar cortex as well as posterior cortical regions in performing verbal working memory tasks. A further study by the research group (Petrides, Alivisatos, Evans, & Meyer, 1993b) confirmed the results of a bilateral activity in the middle dorsolateral prefrontal cortex, as well as the anterior cingulate and posterior-parietal cortex. The relevance of the dorsolateral prefrontal cortex was also confirmed by D’Esposito, Postle, Ballard and Lease (1999). Previously, Fuster (1989) assumed that this area is able to integrate events separated in time and application as well as storing representative knowledge to generate a motor response. The postulated bilateral activity was also confirmed by Cohen, Forman, Braver, Casey, Servan-Schreiber and Noll (1994). In their study, participants were asked to perform a ‘n-back task’ while being scanned by functional magnetic resonance imaging. The results showed an additional activity in the middle, inferior and frontal regions. Furthermore, Goldman-Rakic (1998) suggested that working memory is related to regions in the prefrontal cortex that interact with posterior regions as a multimodal and area-specific network. In addition, activity in the prefrontal cortex is also reported to be related to the difficulty of working memory tasks (Braver, Cohen, Nystrom, Jonides, Smith, & Noll, 1997; Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; D’Esposito, Aguirre, Zarahn, Ballard, Shin, & Lease, 1998; Rypma et al., 1999). Focusing on working memory tasks without demanding executive processes, D’Esposito et al. (1998) and Owen (1997) reported increased activity in the ventral prefrontal cortex, whereas a manipulation of information was associated with activity in the middle dorsolateral prefrontal cortex (D’Esposito et al., 1998; Owen, 1997). Within their meta-analysis, Wager and Smith (2003) suggest an allocation of working memory to the following cortical regions:

- Association between frontal cortex and the kind of execution. Furthermore, executive demands are reliable to the activity in the frontal cortex.
- Association between superior frontal cortex and working memory tasks including the sequential updating and prioritization of information.
- Association between inferior frontal cortex and manipulating information within working memory. Furthermore, additional processes like mental operations, cognitive flexibility and inhibition also seem to play a highly significant role in inferior frontal cortex activity.
- Association between frontal cortex lateralization and executive demands
- Association between bilateral activity and verbal storage, whereas spatial storage was associated with increased right hemispheric activity.

Updating working memory based on incoming information was investigated by Salmon et al. (1996). Using a phonological short-term memory task as well as a working memory task both resulted in cerebral metabolism differences. While the phonological short-term memory task led to an increase in activity of the lower left supramarginal gyrus and premotor area, the working memory task confirmed the assumed relevance of the mid-dorsolateral prefrontal cortex. A predominantly right activity occurred in the inferior parietal region during the working memory task. Furthermore, the results highlighted the importance of the superior occipital gyrus in the visual short-term memory. Considering the underlying mechanisms of the episodic buffer, a general relation with the right middle temporal lobe is assumed (Rudner, Foo, Rönnberg, & Lunner, 2007; Rudner & Rönnberg, 2006; Rudner & Rönnberg, 2008). Furthermore, Berlingeri et al. (2008) suggested an association between the left anterior hippocampus and the episodic buffer. Their results were based on a study examining two groups of people, one with Alzheimer's disease and one with healthy control.

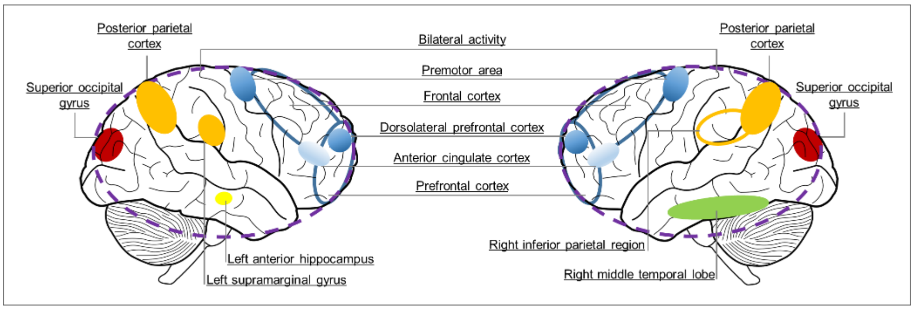


Figure 5 Underlying structures of the working memory.

As mentioned above, Constantinidis and Klingberg (2016) introduced three models. Regarding the human working memory model, the authors reported an association between working memory and a wide range of areas across the brain dependent on the type of stimulus. On the other hand, the authors revealed common activity particularly in a fronto-parietal network during the performance of different working memory tasks. While Constantinidis and Klingberg (2016) investigated only visuo-spatial working memory tasks, Figure 5 includes both verbal and visuo-spatial working memory tasks.

2.2.3. Shifting / Set-shifting

Shifting back and forth between multiple tasks, operations or mental sets is becoming increasingly relevant in the modern society (Monsell, 1996). We call friends while answering e-mails and looking after our children; we work on the computer, while searching the desk for a document and having lunch. These are only two out of numerous daily situations in which the ability to switch or shift between different sets becomes highly relevant. Thereby, the task-switching paradigm was introduced by Jersild (1927), who investigated students working through a list of items, either repeating one task or alternating between two. After nearly 50 years, Biederman (1972) revived Jersild's paradigm by using discrete reaction-time measurements. Along with Biederman's work and some other pioneering studies (e.g. Biederman, 1973; Shaffer, 1965; Sudevan & Taylor, 1987), task switching became more popular during the mid 1990s. Until now, the paradigm has been used in a more sophisticated way by asking participants to change from using one task set - defined as a series of procedural rules governing the performance - to another (Aron, 2008; Monsell, 2003). In this context, Kiesel et al. (2010) summarized that individuals are slower and make more errors on trials that require switching between the performances of two simple tasks compared to its single performance. Furthermore, the switch cost is commonly used for measuring the ability of task switching and it is computed by subtracting the average reaction time of non-switch trials from the average reaction time of switching trials (Aron, 2008). While a higher switch frequency leads to a lower switch cost (Mayr, Diedrichsen, Ivry & Keele, 2006; Monsell & Mizon 2006), Kray and Lindenberger (2000) further differentiated between 'general' and 'specific' switch cost. Here, the authors defined 'general' switch cost as the difference between reaction times on trials with switch blocks and reaction times on trials with homogeneous blocks that do not contain switching, whereas 'specific' switch cost is described as the difference between reaction time on the switch trial and reaction time on repeat trials during switch blocks. Considering the relationship between shifting and the central executive, it is assumed that the ability to shift between tasks or mental sets must be seen as highly dependent on the function of executive control (Monsell, 2003; Norman & Shallice, 1986). Additional evidence comes from dual-task experiments that identified increasing impairments in task-switching performance with increasing demand on the executive control component (e.g. Baddeley, Chincotta, & Adlam, 2001a). By contrast, some investigators reported a lack of relation between working memory / executive control and task switching (Allport, Styles, & Hsieh, 1994; Oberauer, Süß, Wilhelm & Wittman, 2003; Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000; Wylie & Allport, 2000). Investigating the relation between inhibition and switching, Philipp and Koch (2006) reported, a larger task-set inhibition under high switch probability conditions compared to low switch probability conditions. Based on their results, the authors suggested that the balance of activation and inhibition in task switching is affected by the occurrence of task repetitions.

Focusing on the underlying mechanisms of shifting / set-shifting, early patient studies suggested an association between frontal lobe impairments and shifting between mental sets (Luria, 1966; Stuss, & Benson, 1986). In this context, Aron (2007) summarized that patients with right inferior frontal cortex lesions showed an increased switching cost. Furthermore, Nachev, Wydell, O'Neill, Husain and Kennard (2007) and Floden and Stuss (2006) revealed impairments in stopping one response and performing another in a patient with pre-supplementary motor area damage. Their findings were confirmed by a non-human study conducted by Isoda and Hikosaka (2007). Here, the authors reported an increased activity of the pre-supplementary motor area associated with switch trials in monkeys. Along with clinical and non-human trials, various imaging studies provide evidence of the neural mechanisms responsible for the ability to shift. Monsell (2003) reported an increased activity in medial and lateral regions of the prefrontal cortex as well as in the parietal lobe, the cerebellum, and other subcortical regions in performing switching tasks. Further studies revealed increased activity in the dorsolateral prefrontal cortex and posterior-parietal areas (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Garavan, Ross, Li, & Stein, 2000; Kimberg, Aguirre, & D'Esposito, 2000; Sohn, Ursu, Anderson, Stenger, & Carter, 2000). Meyer et al. (1998) and MacDonald, Cohen, Stenger and Carter (2000) highlighted the left dorsolateral prefrontal cortex in task switching. Differentiating between shifting of visual attention and more executive oriented shifts, Posner and Raichle (1994) showed that shifting visual attention might be regulated primarily by the parietal lobes and the mid-brain, whereas more executive-oriented shifts may be regulated primarily by the frontal lobes, including the anterior cingulate. Along with frontal lobe structures, Moulden, Picton, Meiran, Stuss, Riera and Valdes-Sosa (1998) indicated occipital and parietal regions involved in shifting between two tasks by using event-related potentials. Additionally, Sylvester et al. (2003) reported increased activity in the parietal and occipital lobe, preferentially involved in switching of attention between mental counts. The findings based on imaging studies are additionally summarized in Figure 6.

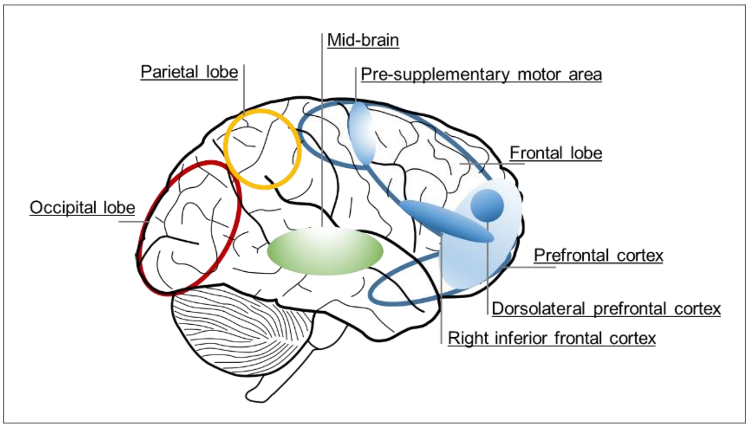


Figure 6 Underlying structures of shifting / set-shifting.

2.2.4. Age-related differences in executive functions

Impairments in executive functions are frequently reported in brain injuries, such as lesions or trauma (e.g. Varney & Menefee, 1993), mental illness (e.g. Galdi, 1993) and pathological disturbances in the brain metabolism such as Alzheimer's disease or phenylketonuria (e.g. Welsh, Pennington, Ozonoff, Rouse, & McCabe, 1990; Lafleche & Albert, 1995) as well as in healthy older adults (e.g. Brennan, Welsh, & Fisher, 1997; Royall, Palmer, Chiodo, & Polk, 2004). Growing evidence of impaired executive functions in healthy elderly subjects comes from various neuropsychological studies reporting inter alia difficulties in problem-solving (including flexible thinking and cognitive shifting), impaired response inhibition, and impaired creative thinking (Dorfman, 1998, for review). In this context, Brennan et al. (1997) investigated three age groups (group one: mean 65 years; group two: mean 75 years; group three: mean 19 years), by using the ‘Tower of Hanoi’. Similar findings were identified for group one and three, whereas group two significantly differed. Furthermore, with increasing complexity (4-disk) young adults showed superior performance on average, compared to young elderly or older elderly participants. These results were confirmed by Rönnlund, Lövdén and Nilsson (2001), within a larger sample size of N = 2,798, ranging from 35 to 85 years. Another task that is frequently used for investigating age-related differences in executive functions is represented by the Wisconsin Card Sorting Test. For example, Mejia, Pineda, Alvarez & Ardila (1998) reported age-related differences within a sample size of 60 participants with a mean age of 69.66 years.

Considering age-related differences in working memory, Craik (1994) reported a decline across the adult lifespan. Furthermore, Park et al. (1996) and Park, Lautenschlager, Hedden, Davidson, Smith and Smith (2002) revealed a linear life-long decline with little or no evidence of accelerated decline in the later decades. Focusing on perceptual speed and working memory, Park et al. (1996) investigated 301 participants ranging from 20 to 90 years. The results indicated that both processing speed and working memory depend on age-associated changes as well as the type of memory task. A further study conducted by Park et al. (2002) focused short-term, working, and long-term memory in 345 adults (ranging from 20 to 92 years). Using tasks of visuo-spatial and verbal working memory, an age-related decline in memory processes was shown continuously across the adult life span. Age-related differences in the ability to inhibit were first examined by Comalli, Wapner and Werner (1962). Investigating 235 people ranging from 7 to 80 years, the authors reported an u-shaped curve in which the magnitude of the effect increased among the elderly. In a later study, Williams, Ponesse, Schachar, Logan and Tannock (1999) used the stop-signal procedure to investigate age-related differences in a group ranging from 6 to 81 years

(N = 275). Although the results failed to confirm a u-shaped curve of age-related changes, the authors reported an age-related speeding of go-signal reaction time throughout childhood, followed by a marked slowing throughout adulthood.

Focusing on age-related differences in shifting / set-shifting, Lezak (1995) reported that elderly do not necessarily reach the level of ‘dysfunction’, but rather show increased difficulties. A u-shaped function for switching cost with larger costs found for young children and older adults (N = 152 ranging from 7 to 82 years) was identified by Cepeda, Kramer and Gonzalez de Sather (2001). Within three experiments Meiran, Gotler and Perlman (2001) revealed an increased switching cost with increasing age. Furthermore, the authors discussed their results in relation to the underlying neural mechanisms, especially the prefrontal cortex. Numerous other authors have also discussed a frontal deterioration responsible for impairments in executive functions of the elderly (e.g. Gunning-Dixon & Raz, 2003; Burke & Barnes, 2006). Furthermore, MacPherson, Phillips and Della Sala (2002) differentiated between dorsolateral prefrontal and ventromedial prefrontal dysfunction. Participants (N = 90 ranging from 20 to 80 years) completed three executive function tasks, dependent on dorsolateral prefrontal dysfunction, and three tasks of emotion and social decision making, dependent on ventromedial prefrontal dysfunction. The participants showed an age-related effect in all dorsolateral prefrontal dysfunction tasks but not in tasks dependent on ventromedial prefrontal dysfunction. Age-associated differences in white matter (e.g. Ylikoski, Erkinjuntti, Raininko, Sarna, Sulkava, & Tilvis, 1995, Head et al., 2004) were also associated with a decline in executive functions (Gunning-Dixon & Raz, 2003, for review). Along with white matter associations, Buckner (2004) demonstrated a relationship between changes in gray matter and a decline in performance on executive functions.

With a glance back to the present chapter, it should be noted that executive functions are a highly complex construct of functions responsible for monitoring, regulating and coordinating the execution of goal-directed behavior. Although there is an increased need for further research in the field of executive functions, the three main processes of inhibition, working memory and shifting are frequently investigated in previous studies. Here, the present chapter has highlighted the most frequently-used paradigms such as the go-/nogo task in the context of inhibition, as well as also models such as Baddeleys’ model of working memory. Behavioral aspects of the main processes of executive functions were supplemented in terms of the underlying mechanism. Here, numerous studies proposed that it is probably unrealistic to expect a precise one-to-one correspondence between executive functions and discrete neuroanatomical structures (e.g. Anderson, Damasio, Jones, &

Tranel, 1991; Mountain & Snow, 1993; Reitan & Wolfson, 1994, 1995; Shallice & Burgess, 1991). Based on previous studies, I suggest that the frontal lobe - and particularly the prefrontal cortex - must be seen as an important substrate for executive functions.

2.3. Decision making

Generally known as a process of choosing between desirable alternatives based on their relative value of consequences (e.g. Balleine, 2007; Edwards, 1954; Fond et al., 2013), Benjamin Franklin described the way of making decisions as follows:

'…my way is, to divide half a sheet of paper by a line into two columns, writing over the one pro, and over the other con. Then during three or four days' consideration I put down under the different heads short hints of the different motives that at different times occur to me for or against the measure. When I have thus got them all together in one view, I endeavor to estimate their respective weights; and where I find two, one on each side, that seem equal, I strike them both out: If I find a reason pro equal to some two reasons con, I strike out the three. If I judge some two reasons con equal to some three reasons pro, I strike out the five; and thus proceeding I find at length where the balance lies; and if after a day or two of farther consideration nothing new that is of importance occurs on either side, I come to a determination accordingly.' [Letter to Joseph Priestley, London, September 19, 1772]

Today, we make decisions 100 to 1,000 times per day or even more in complex scientific, technical, economical, and leadership situations, as well as almost every situation of daily living. While Benjamin Franklin reflected upon his own process of decision making, the present chapter starts by reviewing three of the most common theories / perspectives in this context: the dual-theory, the somatic-marker hypothesis and the differentiation between decision making under objective and ambiguous risk (see Figure 7).

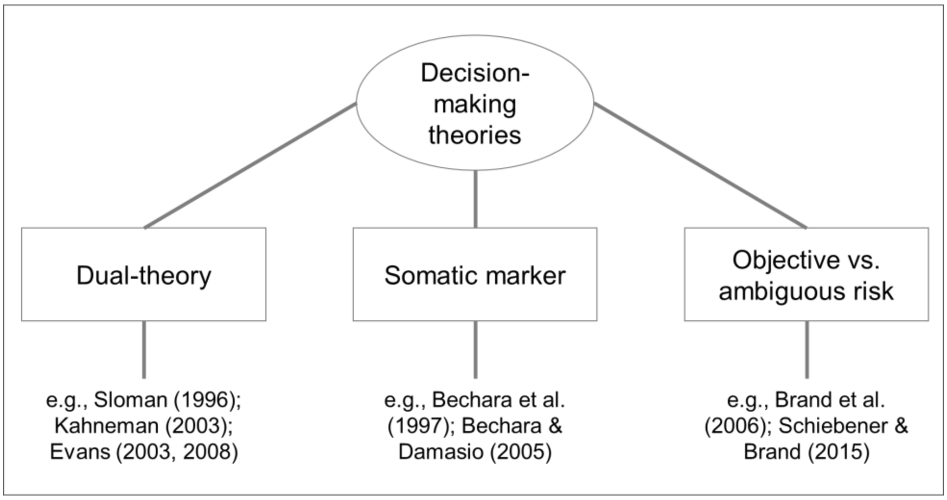


Figure 7 Theories of decision making.

Becoming increasingly popular due to Kahneman's bestseller 'Thinking Fast and Slow', the dual-theory offers a basic differentiation between deliberative and intuitive strategies of decision making (e.g. Kahneman, 2003; Epstein, Pacini, Denes-Raj, & Heier, 1996; Evans, 2003). While the idea of two distinct kinds of reasoning has been described as long as philosophers and psychologists have written about the nature of human thoughts (Evans, 2003), today the two systems are described as implicit and explicit (Evans & Over, 1996; Reber, 1993), impulsive and reflective (Bechara, 2005) or system one and system two (Stanovich, 1999; Stanovich & West, 2000). Therbey, system one could be seen as rapid, parallel and automatic in nature and thus described as intuitive, whereas system two is characterized by being slow, sequential in nature and making use of the central working memory (Baddeley, 2000; Oaksford & Chater, 2001). In addition, system two permits abstract hypothetical thinking that cannot be achieved by system one (Baddeley, 2000; Evans, 2003). Furthermore, Bechara, Damasio, Tranel and Damasio (1997) postulated that decisions are often influenced by impulsive strategies of system one. These biases may be experienced as 'hunches, guesses, or gut feelings' associated with liking or disliking a decision option (Bechara et al., 1997). In recent literature, dual-process models have been criticized for the strict separation of the systems, for potential theoretically wrong conclusions and being considered as unsatisfactory (Evans & Stanovich, 2013, for review). From a neurobiological perspective, there is strong evidence that the brain indeed has particular areas processing emotional impulses and particular areas processing cognitive reflections (Bechara, 2005). However, this evidence would also not support a strict separation of the systems, but rather an interaction between them (Schiebener & Brand, 2015).

A neurobiological perspective was introduced by Damasio, Everitt and Bishop (1996). The somatic marker hypothesis based on the assumption that making advantageous decisions in real life is linked to emotional mechanisms. Therefore, the somatic marker specifies a number of structures and operations required for the normal operation of decision making (Bechara & Damasio, 2005). Caused by the different understandings of emotions, Damasio et al. (1996) used the term ‘somatic’ to refer the collection of body-related responses that hallmark an emotion. Furthermore, Bechara and Damasio proposed that the **ventromedial prefrontal cortex** regulates signals from the body, to support decision making in situations of complexity and uncertainty (e.g. Bechara, Damasio, & Damasio, 2000a; Bechara, Tranel, & Damasio, 2000b; Damasio et al., 1996). Another brain area discussed by the authors comprises the **amygdala**. While the ventromedial prefrontal cortex is described as being necessary to trigger somatic states from secondary inducers, the amygdala is linked to primary inducers. The primary inducers can be understood as innate or learned stimuli that generate pleasurable or aversive states, whereas secondary inducers are thoughts and memories induced by the recall or imagination of an emotional event (Dunn, Dalgleish, & Lawrence, 2006, for review). A further aspect in the somatic marker hypothesis is the differentiation between the ‘body loop’ and the ‘as-if loop’. The ‘body loop’ reflects actions of the body proper, whereas the ‘as-if loop’ is associated with the brain’s representation of the action expected to take place in the body (Bechara & Damasio, 2005; Dunn et al., 2006). Most empirical evidence for the somatic marker hypothesis comes from the Iowa Gambling Task. This experimental paradigm was designed to measure decision making in terms of how it factors ambiguity or uncertainty (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Tranel, Damasio & Damasio, 1996; Dunn et al., 2006, for review). Using the Iowa Gambling Task, Turnbull, Evans, Bunce, Carzolio and O’Connor (2005) reported some synergies to the dual-theory indicated by an intuitive experiential mode, similar to system one in the dual-theory.

Another approach which considering real-life decision making, is proposed in numerous neuropsychological studies differentiating risky decision making into either ambiguous or objective risk (Bechara, 2004; Bechara & Damasio, 2005; Brand, Labudda, & Markowitsch, 2006; Damasio, 1994; Epstein & Wang, 1994; Knight, 1921; Schiebener & Brand, 2015; Schiebener, Wegmann, Pawlikowski, & Brand, 2012; Volz & Gigerenzer, 2012). Decision making under ambiguity, describes decisions without explicit information about the potential outcome and the possible consequences, whereas objective decisions are characterized by providing explicit rules for positive and negative outcomes, their amounts, and probabilities of occurrence. Based on the model of decision making under ambiguity (Bechara et al., 1997) (Figure 8), Brand et al. (2006) suggested an alternative explanation for decision making under objective risk (Figure 9).

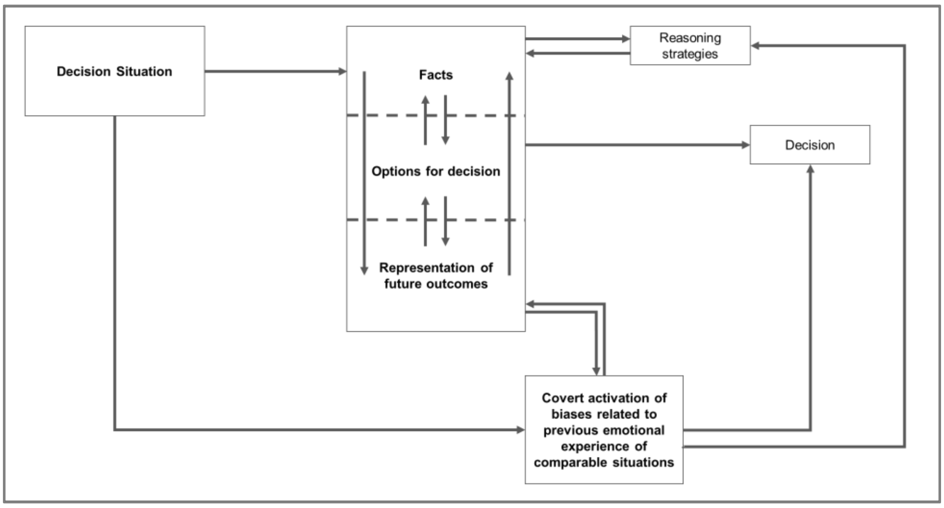


Figure 8 The model of decisions under ambiguity (Bechara et al., 1997).

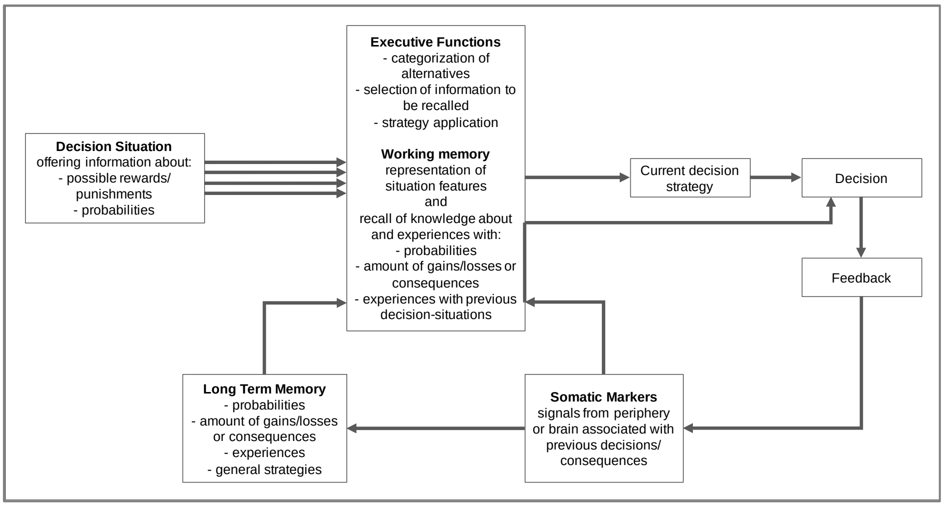


Figure 9 The original model of decision making under objective risk (Brand et al., 2006).

Although the two models look quite similar, there are some differences: in contrast to Bechara et al. (1997), Brand et al. (2006) - for example - proposed a possibility to decide based on rational or cognitive strategies alone. While the relationship between executive functions and decision making is not particularly considered in the model of Bechara et al. (1997), Brand et al. (2006) highlighted the directing role of executive functions in decision making under objective risk. In accordance with dual process theories (Evans 2003; Kahneman 2003; Reyna 2004), both models suggest two ways of decision making that can be triggered in parallel: a cognitive and an emotional way. Here, the emotional way is reported to be influenced by previously chosen options, as suggested in the somatic marker hypothesis. Furthermore, the cognitive way triggers the process of decision making by using strategies of rethinking and probabilities and thus it is strongly associated with long-term memory.

In 2015, the model of Brand et al. (2006) was revised by Schiebener and Brand (2015) following the idea of two interacting systems. The authors suggested that during decision making under objective risk both the impulsive and the reflective system are active, although in most cases one of them is triggered as the leading processing mode. If it is the impulsive system, individuals go by immediate feelings (intuitions, impulses, urge for reward, fear of punishment) constituting a liking / disliking of options. Here, feedback about consequences can trigger immediate reward and punishment reactions and thus can lead to the development of somatic markers. If the reflective system guides the decision-making process, individuals use cognitive control (extract information, deliberate on options, plan, strategize and monitor behavior). In this context, feedback can be used to check and monitor the success of a current decision-making strategy and revise the strategy (Brand, Laier, Pawlikowski, & Markowitsch, 2009a). Whether a decision is made more impulsively or reflectively depends on the relative power of the two systems of a certain individual in a particular situation. For example, if the impulsive system has the upper hand, decisions probably become more spontaneous and riskier. If the reflective system has the upper hand, decisions can become more thought out, planned and guided by ratio considerations (Schiebener & Brand, 2015). Which of the two processing systems become the leading one is affected by several individual and environmental aspects, as well as the situation itself. Thereby, impulsive individuals and people in stressful situations seem to be prone to being guided by the impulsive system. Furthermore, people with better executive functions or after the induction of bad mood seem to be more frequently guided by the reflective system (Epstein et al., 1996; Kahneman & Tversky, 1979; Schiebener & Brand, 2015).

While one of the next sub-chapters will focus on the underlying mechanisms of decision making in further detail, I conclude the present deliberations by providing a brief overview of the suggested mechanisms underlying decision making under ambiguity and objective risk. On the one hand, the prefrontal cortex as well as the fronto striatal loops are described as playing a highly significant role in both ambiguous and objective decision making under risk. On the other hand, Brand et al. (2006) suggested, that decision making under objective risk depends on the ventromedial prefrontal cortex, whereas decision making under ambiguity seems to be more strongly related to the limbic loop and the orbital or ventromedial part of the prefrontal cortex.

2.3.1. Measuring humans’ decision making

In the past, many researchers have tried to quantify the process of decision making, by using various tests and assessments. This sub-chapter aims to provide an overview of some of the most commonly-used ones.

Within the *Iowa Gambling Task* (Bechara et al., 1994) - which is classified as measuring decision making under ambiguity - participants have to make a series of choices, altogether 100 times from four decks of cards. While the decks have different characteristics regarding gains and losses, the actual computerized version did not differ from the originally administered, using decks of paper cards (Bechara et al. 2000b; Bowman, Evans, & Turnbull, 2005). The Iowa Gambling Task is reported to specifically activate the ventromedial prefrontal cortex (Bechara et al., 1994), which is confirmed by numerous lesion studies (Anderson, Bechara, Damasio, Tranel, & Damasio, 1999; Bechara, 2003; Bechara, Damasio, Tranel, & Anderson, 1998; Bechara & Damasio, 2002; Bechara et al., 2000b; Buelow & Suhr, 2009; Fellows, 2004) as well as functional neuroimaging studies (Adinoff et al. 2003; Bolla et al. 2003; Ernst et al. 2002; Tucker, Potenza, Beauvais, Browndyke, Gottschalk, & Kosten, 2004; Windmann et al., 2006). By contrast, Fellows and Farah (2005) showed impairments in the Iowa Gambling Task among individuals with both ventromedial and dorsolateral prefrontal cortex lesions. Along with the findings of the prefrontal regions, individuals with amygdala damage also showed impairments in the Iowa Gambling Task (Bechara, Damasio, Damasio, & Lee, 1999; Brand, Grabenhorst, Starcke, Vandekerckhove, & Markowitsch, 2007b; Brand, Recknor, Grabenhorst, & Bechara, 2007b), although no effects were reported in people with occipital or temporal lobe damage (Bechara, 2004). During recent years, the Iowa Gambling Task has been used in a wide range of patient groups. Impaired performance has been reported - inter alia - among patients with orbitofrontal/ventromedial prefrontal cortex lesions (e.g. Manes, Sahakian, Clark, Rogers, Antoun, Atiken & Robbins, 2002), frontal dysfunctions due to substance addiction (e.g. Bechara & Martin, 2004), schizophrenia (e.g. Shurman, Horan, & Nuechterlein, 2005), obsessive compulsive disorder (e.g. Cavedini, Riboldi, D’Annucci, Belotti, Cisima, & Bellodi, 2002), attention-deficit/hyperactivity disorder (e.g. Malloy-Diniz, Fuentes, Leite, Correa, & Bechara, 2007), pathological gambling (e.g. Linnet, Røjskjær, Nygaard, & Maher, 2006), anorexia nervosa (e.g. Cavedini et al., 2004), Parkinson’s and Huntington’s disease (e.g. Thiel, Hilker, Kessler, Habedank, Herholz, & Heiss, 2003), chronic pain (e.g. Apkarian et al., 2004) and HIV positive substance-dependent males (Hardy, Hinkin, Castellon, Levine, & Lam, 2006).

The *Game of Dice Task* was developed to measure decision making under objective risk. Within the task, participants are provided with explicit information about the potential consequences of different options and their subsequent probabilities (Brand, Fujiwara, Borsutzky, Kalbe, Kesler, & Markowitsch, 2005). In contrast to the Iowa Gambling Task - which is predominantly attributed to either natural or heuristic, or simply to system one (Epstein et al., 1996; Evans, 2003; Kahneman, 2003; Kahneman & Frederick, 2007) - decisions in the Game of Dice Task are mostly referred to the rational-analytical system (or system two). While more detailed information about the task will be provided within the methods of the third experiment, the following paragraph reviews existing findings in the context of the Game of Dice Task.

The reported relevance of executive functions in decision making under objective risk are based inter alia on the numerous findings made in the context of the Game of Dice Task (Brand et al., 2005; Brand et al., 2007b; Brand, Roth-Bauer, Driessen, & Markowitsch, 2008; Brand et al., 2009a; Euteneuer et al., 2009; Schiebener, Zamarian, Delazen, & Brand, 2011; Schiebener et al., 2012; Schiebener, Wegmann, Pawlikowski & Brand, 2013; Schiebener, Wegmann, Gathmann, Laier, Pawlikowski, & Brand, 2014). Here, Brand et al. (2007b), Brand et al. (2009a) as well as Schiebener et al. (2011) showed that poorer decisions in the Game of Dice Task are associated with lower executive functioning. Furthermore, Schiebener et al. (2012) reported the influence of subjects' executive functions on decision-making behavior in the context of anchor effects. The authors revealed larger effects of a simultaneously-presented anchors (a fictitious top 10 list) on the performance of the Game of Dice Task among people with lower, compared to higher levels of executive functions. Investigating the influence of general control, concept formation and monitoring on Game of Dice Task performance, Schiebener et al. (2014) found that general control plays a key role in decision making under objective risk. Along with healthy subjects, numerous studies of the Game of Dice Task have focused on patients with schizophrenia (Fond et al., 2013; Lee et al., 2007), Urbach-Wiethe (Brand et al., 2007a), bulimia nervosa (Brand, Franke Sievert, Jacoby, Markowitsch, & Tuschen-Caffier, 2007c), Korsakoff's syndrome (Brand, Pawlikowski, Labudda, Laier, von Rothkirch, & Markowitsch, 2009b), attention-deficit/hyperactivity disorder (Drechsler, Rizzo, & Steinhauser, 2008) as well as neurodegenerative diseases (Gleichgerrcht, Ibáñez, Roca, Torralva, & Manes, 2010). Furthermore, the relevance of executive functions in performing the Game of Dice Task also becomes obvious in the context of patients. For example, Brand et al. (2008) showed a higher risk-taking behavior in the Game of Dice Task with reduced executive functions among patients with opiate dependency. Furthermore, Euteneuer et al. (2009) demonstrated a correlation between executive dysfunctions and the Game of Dice Task, but not with Iowa

Gambling Task performance among patients with Parkinson’s disease. Combining the Game of Dice Task and a 2-back task, Gathmann, Schiebener, Wolf and Brand (2015) demonstrated the relevance of concept formation and monitoring in simultaneous decision making under objective risk and performing a working memory task. Furthermore, Schiebener et al. (2013) reported that people with high abilities in working memory and executive functions do not need advice to make frequent advantageous decisions, whereas those with lower abilities benefit from the advices. Another correlation often reported in the context of the Game of Dice Task is logical reasoning / intelligence (Brand et al., 2009a; Brand & Schiebener, 2013). Here, Brand et al. (2009a) discussed the influence of intelligence and strategy application in performing the Game of Dice Task with and without feedback. Furthermore, participants’ intelligence and strategy application is found to influence the effects of feedback in performing the Game of Dice Task (Brand et al., 2009a; Schiebener et al., 2011).

The behavioral studies of the Game of Dice Task are supplemented by neuroimaging findings reporting a relationship between strategic components and the dorsolateral prefrontal cortex in a modified version of the Game of Dice Task (Labudda, Woermann, Mertens, Pohlmann-Eden, Markowitsch, & Brand, 2008). Furthermore, Labudda et al. (2008) revealed a pattern comprising the prefrontal cortex, posterior-parietal lobe, anterior cingulate and right lingual gyrus related to the integration of information about probabilities and incentives. This pattern is assumed to be activated due to the involvement of executive functions, conflict detection mechanisms and arithmetic operations. Focusing on age-related differences, Brand and Schiebener (2013) investigated the interactions of aging and cognitive functions in the context of performing the Game of Dice Task. A large sample size of 538 participants - ranging from 18 to 80 years - were asked to perform the Game of Dice Task, the Iowa Gambling Task as well as tasks measuring logical thinking and executive functions. Regarding the Game of Dice Task, older participants with good executive functioning performed well, whereas older participants with impaired executive functions made more risky choices. Therefore, the authors concluded that age and cognitive functions act in concert of predicting decision-making performance. Regarding gender-related influences, the same study (Brand & Schiebener, 2013) revealed no effects, which is in accordance with Starcke, Wolf, Markowitsch and Brand (2008). However, Starcke et al. (2008) focused on examining whether decision making could be affected by anticipatory stress. In this context, the authors reported that participants under stress scored significantly lower than the comparison group, while the performance of the Game of Dice Task was negatively correlated with an increased level of cortisol. Pabst, Brand and Wolf (2013a) specified the influence of stress regarding the temporal development. Participants performed the

Game of Dice Task 5, 18, or 28 min after the application of the Trier Social Stress Test. The results indicated an improvement in decision making among the 5 and 18 min stress groups, while the 28 min stress group showed a more risky decision behavior compared to controls. Based on their findings, the authors concluded that a moderate increase in catecholamine enhances decision-making performance, whereas elevated cortisol concentrations may negatively affect decision making. The relevance of individuals' cortisol response in the context of decision making was also highlighted by Starcke, Polzer, Wolf, and Brand (2011a). Focusing on moral decision making, the authors revealed a positive correlation between cortisol responses and egoistic decision making in emotional dilemmas. A broader study was conducted by Gathmann et al. (2014a). The authors asked their participants to perform the Game of Dice Task with and without an additional working memory task (2-back task). Furthermore, participants received either the Trier Social Stress Test (stress group) or the placebo Trier Social Stress Test (control group). Using a 7-tesla magnetic resonance imaging, the stress group showed a greater increase in neural activity in the anterior prefrontal cortex when performing the 2-back task simultaneously with the Game of Dice Task compared to its single performance. While the anterior prefrontal cortex is associated with parallel processing, the authors concluded that stress seems to trigger a switch from serial to parallel processing in demanding dual-tasking situations. Another study conducted by Gathmann, Pawlikowski, Schöler and Brand (2014b), investigated the effects of performing the Game of Dice Task and an additional 2-back task with affective pictures (positive, negative and neutral pictures). People who performed the additional 2-back task with affective pictures (especially positive pictures) showed more disadvantageous decisions in the Game of Dice Task compared to those who performed the 2-back task with neutral pictures or simply performed the Game of Dice Task without an additional executive task. These results impressively demonstrate the interaction between executive functions and emotional processing in predicting decision making under objective risk.

Assessing individuals' willingness to place already-accumulated reinforcement at risk, outside a learning context, the *Cambridge Gambling Task* is also classified as measuring decision making under risk (Rogers et al., 1999a). In contrast to the Game of Dice Task, the task differentiates between the single components of a decision and thus measures risk-taking, the quality of decision making, deliberation time, risk adjustment, delay aversion and overall proportion bet (Deakin, Aitken, Robbins & Sahakian, 2004; Rogers et al., 1999a; Rogers et al., 1999b). Performing the Cambridge Gambling Task, participants had to guess whether a yellow token was hidden in a red or blue box. Subsequently, the participants were asked to stake a proportion (i.e., 5%, 25%, 50%, 75%, or 95%) of their points on that decision (Clark, Bechara, Damasio, Aitken, Sahakian, & Robbins, 2008). While the

Game of Dice Task showed no gender differences (Starcke et al., 2008), the Cambridge Gambling Task revealed differences between men and women, albeit only in risk adjustment (van den Bos, Homberg & de Visser, 2013). In the context of stress and decision making, Porcelli and Delgado (2009) observed a stress related affection of risk-taking behavior in a modified Cambridge Gambling Task. Given that decision-makers fell back on automatized reactions to risk under the influence of disruptive stress, the authors highlighted the consistency with dual-process approaches. In the past, the Cambridge Gambling Task was reported to be sensitive to many pathological states including attention-deficit/hyperactivity disorder (DeVito et al., 2008), borderline personality disorder (Bazanis et al., 2002), Huntington's disease (Watkins, Rogers, Lawrence, Sahakian, Rosser, & Robbins, 2000) as well as age-related differences (Deakin et al., 2004). Further evidence from patient studies, highlights the relevance of frontal areas in performing the Cambridge Gambling Task (e.g. Clark et al., 2008). Additionally, the role of the ventro-medial prefrontal cortex and insular regions in this context was highlighted by the authors.

While the Iowa Gambling Task, the Game of Dice Task, and the Cambridge Gambling task are most commonly used in decision-making studies, many other tests / assessments have been previously reported in this context. In order to ensure a better understanding of the neurophysiological findings reported in the next sub-chapter, Table 1 summarizes further paradigms with their classification to either decision making under risk, ambiguity, uncertainty or others and provides a brief characterization and some key findings.

Table 1 Tests for quantifying decision making.

Assessments	**References**	**Classified**	**Aims/Description/ Characteristics**	**Few results**
Columbia Card Task	Figner & Voelki, 2004; Figner et al., 2009; Figner & Weber, 2011	Decision making under objective risk	Development changes and individual differences in healthy individuals across the life span and in populations such as substance users	Adolescents showed more risky behavior than adults
Balloon Analogue Risk Task	Lejuez et al., 2002; Lighthall et al., 2009	Decision making under objective risk	Participants are presented with a balloon and offered the chance to earn money by pumping the balloon up by clicking a button	Gender differences as well as the influence of stress are reported
Cups Task	Levin & Hart, 2003; Levin et al., 2007; Weller et al., 2011; Levin et al., 2014;	Decision making under objective risk	Designed to provide a simple and direct way of depicting probability by merely counting the number of cups from which to choose in risky decision-making	Children showed higher risk-taking behavior in the gain domain than adults
The Ultimatum Game	Güth et al., 1982; Sanfey et al., 2003	Economic decision making	Illustrates limitations of standard economical decisions by giving participants the opportunity to split money or not	Unfair offers elicited activity in brain areas related to both emotion and cognition

Probability Associated Gambling	Zamarian et al., 2007; Sinz et al., 2008; Zamarian et al., 2008	Decision making under objective risk	Requires participants to assess the probability of the possible gains and losses, and to flexibly adapt their decision strategy to changes in the decision situation.	Patients with Alzheimer disease showed less advantageous behavior
Risky Gains Task	Reske et al., 2015	Decision making under objective risk	In two subsequent gambles on 96 trials, participants could gamble the safe option (cash in 20 cents) for double or nothing, to gain 40 or, in the potential second gamble, 80 cents (“risky” decisions).	Differences in activated structures between occasional stimulant users and healthy controls during task performance
Wheel of Fortune Task	Haffke & Hübner, 2014; Ernst et al., 2004	Decision making under objective risk	Participants had to decide whether they wanted to play the lottery with the higher winning probability or the one with the higher potential gain	Performing without feedback, led to decisions with higher winning probability, and ignoring the potential gains
Lane Risk Taking Task	Lane & Cherek, 2000; Lane et al., 2005	Decision making under objective risk	The task presented discrete trials in which the subject was forced to choose between two response options, labeled C and A on the response panel	Participants with a high-risk history showed more often risky decisions, had lower overall earnings, and were more likely to persist in making risky responses following a single gain on the risky option
Rogers Decision-Making Task	Rogers et al., 1999b; Fishbein et al., 2005	Decision making under objective risk	Participants were told that the computer had hidden a yellow token inside one of the red or blue boxes (six in total with different distribution) and that they had to decide whether this token was hidden inside a red or a blue box	Drug abusers showed greater risk taking and heightened sensitivity to rewards than control subjects
Two-choice prediction task	Paulus, 1997; Paulus et al., 2003a	Decision making under uncertainty	Participants had to predict whether a car will be shown on the left or right side of the computer screen	Participants showed an increase in response switching as a function of error rate
Balls in a bottle task	Phillips & Edwards, 1966; Blackwood et al., 2004	Decision making under uncertainty	Participants are asked to imagine two bottles containing balls of two different colors in varying proportions. They had to guess from which bottle a particular sequence of balls is likely to have been drawn	
Jumping to Conclusion Task	Esslinger et al., 2013; Demanuele et al., 2015	Decision making under ambiguity	Participants view fish of two colors jumping and had to decide from which of two lakes, containing fixed ratios of each type of fish, they were coming	Probabilistic reasoning and executive functions share neural substrates
Speed-Accuracy Trade-Of Task	Ivanoff et al., 2008	Perceptual decisions	A cue instructed participants to heed the speed or accuracy of their decisions at the onset of a block of seven trials	Tradeoff in performance between response speed and accuracy

2.3.2. Decision making and its underlying mechanisms

While numerous previous neuroimaging studies of decision making have addressed disease-related differences, this chapter predominantly concentrates on findings based on healthy participants. Although Bolla et al. (2003) focused on the effects of cocaine abuse, healthy controls showed an increased right orbitofrontal cortex activity in performing the Iowa Gambling Task. Based on a group comparison, the authors concluded that orbitofrontal activity reflects differences in the anticipation of reward, whereas activity in the dorsolateral prefrontal and medial prefrontal cortex is anticipated with planning and working memory. Another study conducted by Bolla, Eldreth, Matochik and Cadet (2005) investigated the effects of abstinent of substance abuse (marijuana) on decision making under ambiguity. Healthy controls showed a decision-related activity of the right dorsolateral prefrontal cortex, right lateral orbitofrontal cortex, and left cerebellum. The relevance of the dorsolateral prefrontal cortex in decision making under ambiguity was confirmed by Demanuele, Kirsch, Esslinger, Zink, Meyer-Lindenberg and Durstewitz (2015), using the Jumping to Conclusion Task. Furthermore, the authors reported that the dorsolateral prefrontal cortex as well as the anterior cingulate cortex contributed more to the decision-making phase, whereas the orbitofrontal cortex must be seen as being more involved in choice evaluation and uncertainty feedback. The involvement of the orbitofrontal cortex in decisions under ambiguity was also reported by Hsu, Bhatt, Adolphs, Tranel and Camerer (2005). While playing a card game with missing relevant information (decision under ambiguity), participants showed a positive correlation with the amygdala and a negative correlation with the striatal system. Performing the Iowa Gambling Task, participants in the study conducted by Li, Lu, D’argembeau, Ng and Bechara (2010) showed increased activity in both dorsolateral as well as orbitofrontal structures. Further activity was reported in the insula, the posterior cingulate cortex, the ventromedial prefrontal cortex, the ventral striatum, and the anterior cingulate. Along with a sole representation of the activated structures, the authors attributed single aspects of the decision process. Therefore, the dorsolateral prefrontal cortex was attributed to working memory, the insula and posterior cingulate cortex to the representation of emotional states, the mesial orbitofrontal and ventromedial prefrontal cortex to coupling working memory and the representation of emotional states. Furthermore, the ventral striatum and anterior cingulate to implement behavioral decisions. A single activation of the medial frontal gyrus in performing the Iowa Gambling Task was revealed by Fukui, Murai, Fukuyama, Hayashi and Hanakawa (2005). Furthermore, they reported a significant inter-individual correlation between the task performance and the magnitude of brain activity during task performance. The anterior cingulate cortex seems to play a highly relevant role in decision making under objective risk (e.g. Labudda, Brand, Mertens, Ollech, Markowitsch, & Woermann, 2010), uncertainty (e.g. Paulus, Feinstein, Simmons, & Stein, 2004) and ambiguity (e.g. Demanuele et al., 2015). In decision making under objective risk, increased activity of the anterior cingulate cortex was also reported by Ernst et al. (2002). Using a computerized card game, the authors revealed further activity in the orbital and dorsolateral prefrontal cortex, the insula, the inferior parietal cortex and the cerebellum. Furthermore, the authors reported an association of guessing with left sensory-motor areas and the amygdala, whereas informed decision making activated areas that subserve memory and motor control. Within a further study, Ernst et al. (2004) reported neural activity of single components of decision making using the wheel of fortune task. Within the selection phase, participants showed predominantly recruited regions involved in visuo-spatial attention (occipito-parietal pathway). Conflict monitoring was associated with anterior cingulate activity, manipulation of quantities with parietal cortex activity and preparation for action with activity in premotor areas. Additionally, the anticipation phase was related to regions engaged in reward processes (ventral striatum). Another study revealing increased activity in the anterior cingulate cortex during decision making under objective risk was conducted by Cohen, Heller and Ranganath (2005). While participants chose one out of two options in attempt to win money, increased activity in the anterior cingulate and orbitofrontal cortex was associated with high-risk decisions. Furthermore, the authors reported connectivity patterns inter alia in the amygdala and nucleus accumbens. As already described in the context of the Game of Dice Task, Labudda et al. (2010) revealed increased activity in the lateral prefrontal, anterior cingulate cortex and parietal lobe when integrating relevant information in the decision process. Focusing on the role of the insula in decision making, Xue, Lu, Levin and Bechara (2010) confirmed the findings of increased activity in the anterior cingulate cortex. Furthermore, the authors demonstrated a correlation of insular activity with individuals’ personality trait of urgency. Along with the anterior cingulate, which seems to be generally activated in decision making, the ventromedial part of the prefrontal cortex - which is mentioned as being specifically activated in decisions under objective risk (Brand et al., 2006) - should be focused in detail. Considering patients with ventromedial prefrontal cortex lesions, Clark et al. (2008) reported an increased betting of the odds. Based on their findings, the authors highlighted the role of the ventromedial prefrontal cortex as well as the insular regions in decision making under objective risk. Along with the dorsal and ventral striatum, the anterior cingulate and orbitofrontal cortex, dopaminergic mid-brain regions and the ventrolateral prefrontal cortex, Tom, Fox, Trepel and Poldrack (2007) reported an association between the ventromedial and the anticipation and receipt of monetary rewards. In their study, participants had to decide whether to accept or reject gambles that offered a 50/50 chance.

Implicated in disparate cognitive, affective, and regulatory functions, including interoceptive awareness, emotional responses, and empathic processes (Menon & Uddin, 2010), the insula is another structure that is frequently reported to be activated in decision making under objective risk (Paulus, Rogalsky, Simmons, Feinstein, & Stein et al., 2003b; Preuschoff, Quartz, & Bossaerts, 2008). For example, Paulus et al. (2003b) revealed three main findings: first, participants showed greater right insula activity in ‘risky’ versus ‘safe’ choices; second, the relation of the degree of insula activity was related to the probability of selecting a ‘safe’ response following a punished response; and third, the degree of insula activity correlated with subjects’ degree of harm avoidance and neuroticism. While Paulus et al. (2003b) used the Risky-Gains task, participants in the study conducted by Preuschoff et al. (2008) had to guess whether a second card would be higher or lower than the previous one. In their study, the authors revealed a correlation between early-onset activity in the insula and risk prediction error. Another subcortical structure, frequently reported in decision making under objective risk, is the striatum. More specifically, the ventral striatum is reported to be associated with reward (Ernst et al., 2004; Fliessbach et al., 2007 Tom et al., 2007; Wilbertz et al., 2012), whereas the dorsal part of the striatum is attributed to action selection and initiation through the integration of sensorimotor, cognitive, and motivational/emotional information in decision making under objective risk (Balleine, Delgado, & Hikosaka, 2007; Wilbertz et al., 2012).

Aiming to provide a brief overview of the relevant structures within the process of decision making, I additionally highlight the underlying mechanisms in Figure 10.

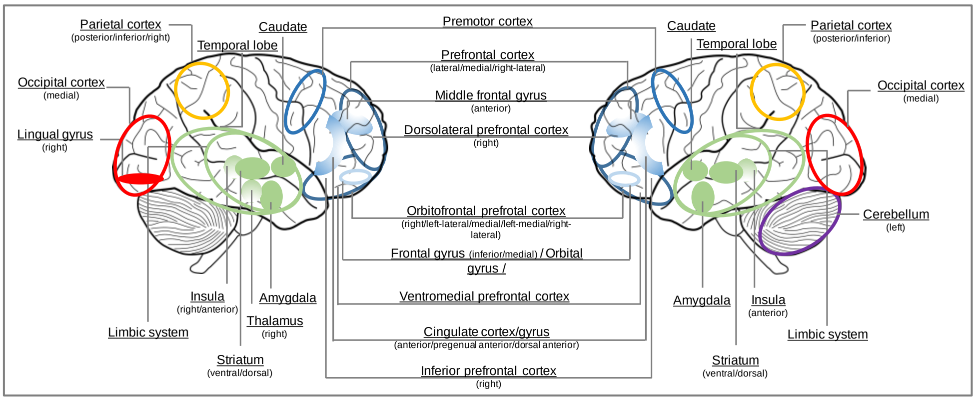


Figure 10 Underlying structures of decision making.

Furthermore, the assignment of respective structures to the different kinds of decisions are additionally summarized in Table 2. Here, the terminologies are used from the respective studies.

Table 2 Underlying structures of decision making.

[assigned to objective risk, uncertainty, ambiguity, or others]

Activated structures	Objective risk	Uncertainty	Ambiguity	Others
Prefrontal cortex		30)		
Medial prefrontal cortex		23), 25), 27), 28)		
Lateral prefrontal cortex	17)			36)
Right lateral prefrontal cortex		24)		
Inferior prefrontal cortex		21)		
Right inferior prefrontal cortex	1)			
Dorsolateral prefrontal cortex	2), 11)	20), 23)	35)	37)
Right dorsolateral prefrontal cortex	8), 14)		32)	
Medial part of lateral prefrontal cortex	15)			
Ventromedial prefrontal cortex	10), 12)			
Right orbitofrontal prefrontal cortex	1)			
Orbital prefrontal cortex	2)			
Orbital gyrus	1)			
Orbitofrontal cortex	7)	20), 23), 24), 25)	34)	
Right orbitofrontal cortex			31)	
Right lateral orbitofrontal cortex			32)	
Medial orbitofrontal cortex	19)			
Paracingulate orbitolateral cortex	5)			
Right posterior orbitolateral cortex	5)			
Anterior part of the middle frontal gyrus	1)			
Anterior portion of the inferior frontal gyrus	1)			
Anterior cingulate cortex	2), 4), 7), 17), 18)	20), 21), 23), 27)	35)	
Right cingulate gyrus	11)			
Anterior cingulate gyrus	11)			
Dorsal anterior cingulate gyrus				38)
Pregenual anterior cingulate cortex	5)			
Frontal cortex	9)			
Inferior frontal cortex	6)			
Medial frontal cortex	6)	30)		
Medial frontal gyrus			33)	
Premotor cortex		22)		
Limbisches System		26)		
Caudatus		29)		
Amygdala			34)	
Right Thalamus	2)			
Striatum	16)		34)	
Ventral Striatum	4), 10), 19)			
Dorsal Striatum	19)			
Insula	2), 12), 13), 18)	28)		
Insula right	3)			
Anterior Insula				37)
Nucleus accumbens caudate	6)			
Temporal cortex		23)		
Superior temporal gyrus	6)			
Middle temporal gyrus	6)			
Fronto-parietal system		26)		
Parietal cortex	4), 17)	20), 29), 30)		
Right parietal cortex		23)		
Posterior parietal lobe	11)	21)		
Inferior parietal cortex	2)	22)		

Occipito-parietal pathways	4)		
Occipital cortex	6)		
Medial occipital cortex		22)	
Cerebellum		22)	
Cerebellum left	2)		32)

1) Rogers et al. (1999b): Computerized risk-taking task; 2) Ernst et al. (2002): Risk-taking task; 3) Paulus et al. (2003b): Risky-Gains task; 4) Ernst et al. (2004): Wheel of fortune task; 5) Rogers et al. (2004): Decision-game (choosing between two simple gambles); 6) Matthews et al. (2004): Lane Risk Taking Task; 7) Cohen et al. (2005): Binary choice task in attempt to win money; 8) Ersche et al. (2005): Cambridge Risk Task; 9) Fishbein et al. (2005): Rogers decision-making task; 10) Tom et al. (2007): Gamble offers 50/50 chance of gaining or losing; 11) Labudda et al. (2008): Game of Dice Task (without feedback); 12) Clark et al. (2008): Cambridge Gamble Task; 13) Preuschoff et al. (2008): Card game (people had to decide whether the second card would be higher or lower than the first); 14) Rao et al. (2008): Balloon Analog Risk Task; 15) Xue et al. (2009): Computerized version of the Cups task; 16) Hsu et al. (2009): 120 self-paced trials (choosing between two simple gambles); 17) Labudda et al. (2010): Game of Dice Task; 18) Xue et al. (2010): Modified Cups Task; 19) Wilbertz et al. (2012): Game of Dice Task & Delay discounting; 20) Paulus et al. (2003a): Two-choice prediction task; 21) Paulus et al. (2003c): Two-choice predicition task; 22) Blackwood et al. (2004): Balls in a bottle task; Personality survey task; 23) Critchley et al. (2001): Two-choice decision-making task; 24) Elliott et al. (1999): Simple card-playing task; 25) O'Doherty et al. (2003): Choice reversal task; 26) Paulus et al. (2001): Two-choice prediction task; 27) Paulus et al. (2004): Two-choice predicition task; 28) Paulus et al. (2005): Rock Paper Scissors computer game; 29) Verney et al. (2003): Two choice prediction task; 30) Yarkoni et al. (2005): Selecting from 1 of 2 decks; 31) Bolla et al. (2003): Iowa Gambling task; 32) Bolla et al. (2005): Iowa Gambling task; 33) Fukui et al. (2005): Iowa Gambling task; 34) Hsu et al. (2005): Betting on one of the two options; 35) Demanuele et al. (2015): Jumping to Conclusions task; 36) Ivanoff et al. (2008): SAT-task; 37) Sanfey et al. (2003): Ultimatum Game; 38) Bush et al. (2002): Reward-based decision making

2.3.3. Age-related differences in decision making

The particular relevance of considering age-related differences in decision making is based inter alia on the increasing age of our world population, especially in most industrialized countries and the important that choices older adults still have to make. Here, biological, emotional and social changes are discussed as being responsible for the differences in decision making among the elderly (Denburg, Recknor, Bechara, & Tranel, 2006). Early findings indicated avoidance strategies and a transfer of responsibility with increasing risk of decisions in older adults (Deber, Kraetschmer, & Irvine, 1996; Wallach & Kogan, 1961). The question concerning the extent to wich risk-taking changes during the process of aging, was addressed in a meta-analysis by Mata, Josef, Samanez-Larkin and Hertwig (2011). Based on 29 studies, the authors highlighted the relevance of task characteristics as well as the process of learning in decision making among older adults. Another review, conducted by Wiesiolek, Foss and Diniz (2014) summarized nine studies investigating decision making and aging using the Iowa Gambling Task. Here, the authors concluded that there is no consensus about age-related differences in decision making, but rather an agreement concerning deficits of the elderly in learning and a tendency towards fewer advantageous choices. Considering the two studies with the largest sample size included in their review (Fein, McGillivray, & Finn, 2007; Wood, Busemeyer, Koling, Cox, & Davis 2005), the lack of consensus in this context becomes obvious. On the one hand, Wood and colleagues

(2005) revealed equal performance throughout the task among both younger (n: 88, age: 22.14±4.47) and older participants (n: 67, age: 77.30±4.61), whereas differences between the two groups were identified in the strategies used by the participants. By contrast, Fein et al. (2007) reported less advantageous decision making among older adults (n: 52, age: 73.7±7.4) compared to their younger counterparts (n: 112, age: 37.8±10.8). Furthermore, a great number of the older participants showed an ‘impaired’ performance of the Iowa Gambling Task. This is in accordance with one of the most commonly cited studies in this context (Denburg, Tranel, & Bechara, 2005). Here, older adults (56 – 85 years) made generally less advantageous decisions compared to a sample of younger adults (26 – 55 years). Furthermore, half of the older participants performed the Iowa Gambling Task in a manner reminiscent of neurological patients with damage to the ventromedial prefrontal cortex. Support for the findings reported by Wood et al. (2005) come from Carvalho, de Oliveira Cardoso, Shneider-Bakos, Kristensen and Fonseca (2012). While older participants (n: 40, age: 67.4±5.02) performed equally in the Iowa Gambling Task, compared to the younger ones (n: 40, age: 25.5±4.7), the authors reported significant differences in the learning curve of the two age groups. In addition to the studies summarized in the review by Wiesiolek et al. (2014), further studies of the Iowa Gambling Task need to be considered in this context. For example, Kovalchik, Camerer, Grether, Plott and Allman (2005) examined different aspects of decision making in a sample of older adults (n: 50, age: 70-95) and younger students (n: 51, age: 18-36). The results indicated similar decision behavior across the two groups. In a series of three studies, Denburg et al. (2007) investigated the hypothesis that some seemingly normal older persons have deficits in reasoning and decision making. The authors found that more than one third of the older adults performed disadvantageously on the Iowa Gambling Task. In a more recent study conducted by Bauer, Timpe, Edmonds, Bechara, Tranel and Denburg (2013), 265 healthy participants ranging from 23 to 88 years performed two versions of the Iowa Gambling Task. The authors reported a significant negative correlation between age and task performance in version one, which requires choosing lower immediate reward, but not in the version two, which requires higher immediate punishment. Furthermore, older participants showed a significantly higher rate of impaired performance in version one, compared to version two. An inverted u-shaped function of Iowa Gambling Task performance was reported across the life span from 5 to 89 years, by Beitz, Salthouse and Davis (2014). The authors reported distinct deficits in children and older adults, as well as a change in decision-making strategies after childhood from erratic behavior to more consistent strategies that promote the expected value of deck choices. Similar findings come from Weller, Levin, & Denburg

(2011), who reported an inverted u-shaped course expected value sensitivity in risky choices increasing from childhood to adulthood, followed by a decrease among the elderly. As already reported in the context of the Game of Dice Task, Brand and Schiebener (2013) indicated age-related differences in a large sample size of 538 participants, ranging from 18 to 80 years. In a more recent study, Schiebener and Brand (2017) highlighted the role of cognitive abilities as a mediator of age-related differences in both the Iowa Gambling Task and Game of Dice Task. Thereby, effects of aging in the performance of the Game of Dice Task were only indicated in the last 60 trials. Additional findings from the Cambridge Gambling Task revealed reduced risk-taking behavior with increasing age (Deakin et al., 2004). Furthermore, older participants showed longer deliberation times, poorer decision making and reduced risk-taking, but no significant changes in delay aversion. By contrast, Zamarian, Sinz, Bonatti, Gamboz, & Delazer (2008) found no differences in task performance between younger and older adults. Within the probability-associated gambling task (decision making under risky conditions), Zamarian et al. (2008) also reported similar task performance among younger and older adults. The authors argued that the missing differences are based on the relatively low emotional impact of the task. Thereby, the emotional impact playing key role in decision making among the elderly is discussed in numerous further studies (e.g. Carstensen, Fung, & Charles, 2003; Carstensen, Isaacowitz, & Charles, 1999; Mather & Johnson, 2000). For example, Carstensen et al. (2003) reported an association between increasing motivation to derive emotional meaning from life and a reduced motivation to expand one’s horizons. Furthermore, the authors suggested that the differences are responsible for the changes in social and environmental choices. Within the study conducted by Mather and Johnson (2000), the authors gave their participants two option choices and asked them to review how they felt about their decisions. Older adults (64-83 years) attributed significantly more positive and fewer negative features to their chosen options. Another aspect used for explaining the occurrence or absence of age-related differences in decision making concerns the applied learning strategies. Especially studies that failed to identify any age-related differences in decision making reported different learning strategies in the elderly (Lamar & Resnick, 2004; MacPherson et al., 2002; Wood et al., 2005). Based on numerous previous works, Beitz et al. (2014) summarized that there is consistent evidence suggesting that some learning-related improvement occurs between childhood and adulthood, which declines among older adults. In this context, Kovalchik and Allman (2006) highlighted the role of reversal learning in older adults’ performance of the Iowa Gambling Task. Furthermore, Denburg et al. (2005) reported that older adults had generally flatter learning curves compared to younger adults, which might be responsible for more advantageous decisions over time.

As reported in the previous chapter concerning executive functions as well as the sub-chapter of decision making, previous works suggested a relationship between age-related differences in executive functions and decision making (e.g. Brand et al., 2009a; Schiebener et al., 2011; Schiebener et al., 2012). While Finucane and colleagues (Finucane & Lees, 2005; Finucane, Mertz, Slovic, & Schmidt, 2005) highlighted that age-related difficulties in decision making are strongly related to a decrease in general cognitive abilities, such as executive functions, memory and speed of information processing, others specify the role of poor executive functions in the elderly regarding a tendency to search for less information compared with young adults before making a decision (Mather, 2006, for review). The relevance of the ventromedial prefrontal cortex as well as the striatum in decision making - as mentioned in the previous sub-chapter - becomes even more evident during the process of aging. For example, Samanez-Larkin, Gibbs, Khanna, Nielsen, Carstensen and Knutson (2007) reported an age-related reduction in striatal activity during loss anticipation, but intact activity during gain anticipation. A relationship between increasing variability in the striatum and increasing age was reported in a further study by Samanez-Larkin, Kuhnen, Yoo and Knutson (2010) in the context of financial decisions. Furthermore, Eppinger, Schuck, Nystrom and Cohen (2013) demonstrated reduced ventromedial prefrontal activity during reward learning in the elderly, compared to younger controls. Using the Iowa Gambling Task, Rogalsky, Vidal, Li and Damasio (2012) reported that older adults engaged the right ventromedial prefrontal cortex during task performance relative to the control task. An age-related increase of ventromedial prefrontal cortex and the striatum activity as well as a more advantageous decision were identified by Halfmann, Hedgcock, Kable and Denburg (2016), using the Iowa Gambling Task. Similar findings come from Halfmann, Hedgcock, Bechara and Denburg (2014), in whose study older adults also showed a more advantageous behavior in the Iowa Gambling Task as well as increased activity in the prefrontal cortex. Using a two-choice prediction paradigm in conjunction with functional magnetic resonance imaging, Hosseini, Rostami, Yomogida, Takahashi, Tsukiura and Kawashima (2010) reported a network of brain regions activated in healthy older adults similar to younger controls. In contrast to others, the authors reported no increase in brain activity, but an age-related decrease in activity of the right inferior parietal lobule. A risky-gains task was performed by twelve younger (age 29.9±6.2 years) and nine older men (age 65.2±4.2 years) in the study of Lee, Leung, Fox, Gao, & Chan (2008), while scanning their brain with a functional magnetic resonance imaging. The authors reported contralateral prefrontal activity particularly in the orbitofrontal cortex as well as increased activity in the right insula of older adults compared to the younger ones. In this context, the influence of the dopaminergic and serotoninergic brain system also needs to be considered.

While Mohr, Li and Heekeren (2010) assumed a relationship based on the findings of decision making and neurotransmitter as well as aging and neurotransmitter, direct evidence comes from Chowdhury et al. (2013) (see also Shohamy & Wimmer, 2013). Here, the authors used L-Dopa to increase dopamine levels in the brain of healthy older participants. The results demonstrated an increased task-based learning rate and task performance as well as activity in the striatum after L-Dopa application. Furthermore, Samanez-Larkin, Mata, Radu, Ballard, Carstensen and McClure (2011) showed that older adults with weaker correlations between activity of regions associated with the mesolimbic dopamine system and expected value make less optimal decisions.

Summarizing the present chapter, first I reviewed three of the most common theories in the context of decision making, namly the dual-theory, the somatic marker hypothesis and the differentiation between objective and ambiguous risk. Highlighting their characteristics, it becomes obvious that some aspects strongly overlap or supplement each other. Considering the emerging paradigms, I supplemented the description of the Iowa Gambling Task, the Game of Dice Task, and the Cambridge Gamblich Task by listing further paradigms, their classification as well as a brief description. In this context, particular attention was paid to the Game of Dice Task. Along with general aspects, the relationship with executive functions, the underlying mechanisms as well as also the influence of diseases, the process of aging, stress, the effects of simultaneously performing an additional task as well as the relevance of emotional aspects was highlighted.

Regarding the underlying neural mechanisms, it can be summarized that the anterior cingulate cortex plays a general role in decision making, whereas the ventromedial part of the prefrontal cortex is specifically activated in decision making under objective risk. Further studies have highlighted the different neural structures related to different phases of decision making. Here, the ventral striatum - for example - is associated with reward and the dorsal striatum with action selection and initiation. The ventromedial prefrontal cortex again becomes apparent during the process of aging. Considering age-related studies of decision making, previous studies have reported controversial findings. However, there is a consensus that learning strategies seem to play a highly relevant role in decision making among older adults. Nonetheless, again executive functions and cognitive abilities are also reported as key aspects in explaining individuals’ decision making.

2.4. Dual-task

Humans' ability to perform two or even more tasks simultaneously, as well as occurring interferences have been considered for more than 100 years in a vast number of studies among numerous fields of interest (e.g. Solomon & Stein, 1896). On the one hand, it is generally assumed that the combination of less-demanding stimuli leads to less interferences. On the other hand, previous studies have reported that well-practiced but relatively complex tasks such as shadowing spoken language while playing the piano (Allport, Antonis, & Reynolds, 1972), writing dictated words while reading a novel (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980) or shadowing a text while typewriting (Shaffer, 1975) can also be performed without or less interferences. Within the present chapter, I will provide a better understanding of the term dual-task by providing an overview of existing theories as well as behavioral and neurophysiological findings.

The most common theories of dual-task include the capacity-sharing theory, the bottleneck theory as well as theories of crosstalk (Figure 11) (Pashler, 1994, for a review).

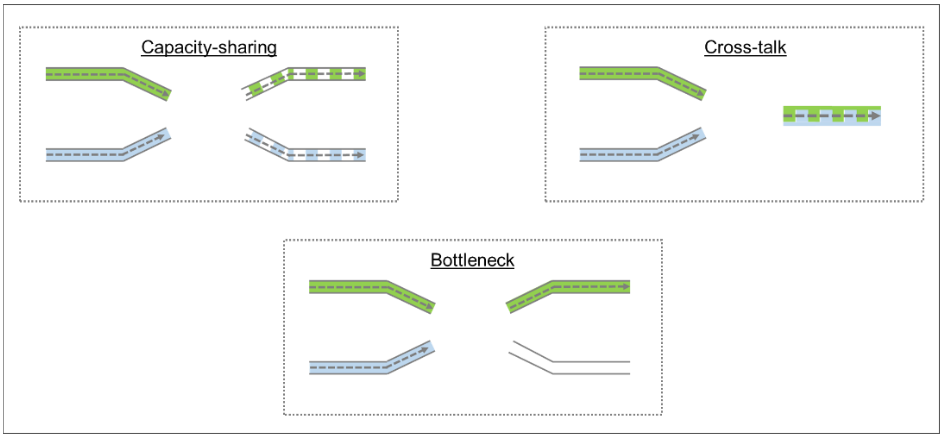


Figure 11 Most common theories of dual-task.

[Capacity-sharing: sharing processing capacity among tasks; Bottleneck: parallel processing might be impossible; Cross-talk: interferences depend on the content of information of performed tasks].

Before focusing on the stated theories of dual-task, two terms, that are inevitable in this context, should be introduced, namely: the so-called 'Psychological Refractory Period' and the 'Stimulus Onset Asynchrony'.

The *'Psychological Refractory Period'* describes a phenomenon that becomes present as soon as two demands occur within a short. Considering the second demand, the arising delay in execution (because the first demand is not already completed) is based on the psychological refractory period. First results showed a delay in response time of the second demand, by using an inter-stimulus interval of 0.2 seconds or less (Telford, 1931; Davis, 1956). In addition to Telford (1931) and Davis (1956) - who used two visual stimuli - Davis (1957) replicated the results by combining a visual and an auditory stimulus. While the psychological refractory period represents the time interval in which a further demand cannot be processed (indicated due to the delay of demand two), the ‘Stimulus Onset Asynchrony’ describes the time between two stimuli and thus is directly linked to the psychological refractory period (see also Figure 12).

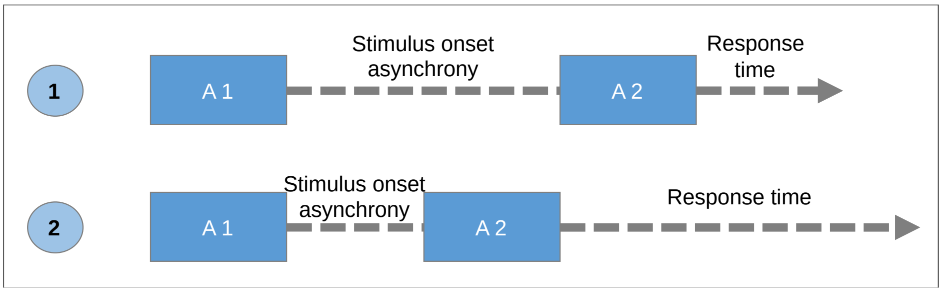


Figure 12 Effects of different stimulus onset asynchrony on response time.

[Case one represents a shorter response time in the second demand (A2), due to a longer stimulus onset asynchrony between stimulus A1 and stimulus A2. Case two describes the opposite and thus illustrates again the relationship between these two components as well as the influence of stimulus onset asynchrony on the response time of the second demand / stimuli (A2)].

In varying the stimulus onset asynchrony, it has been found that a decrease leads to an increased response time of the second task (psychological refractory period-effect) (Kahneman, 1973), whereas the effect on the first task is much smaller (Smith, 1969) and sometimes essentially absent (Pashler & Johnston, 1989, Pasher, 1994). While the stimulus onset asynchrony is used in numerous fields of research (for example, in priming paradigms, see Perea & Gotor, 1997), for the present context the study conducted by Glass et al. (2000) should be focused in greater detail. Within two sub-studies, the authors investigated one group with younger adults (aged 18-26 years) and one with older adults (aged 60-70 years). Experiment one comprised two tasks (task one: one or two tones; task two: written numbers from one to eight) in which participants had to respond manually. The second experiment was equal to the first one, although the difficulty of the first task was increased by additional tones. Across both experiments, the two groups differed in the strategy to coordinate the tasks, the process-specific delay as well as the common delay, which was characterized by the psychological refractory period. Representing an own field of research, both the psychological refractory period as well as the stimulus onset asynchrony were only superficially attended in the present chapter, but will be considered again within the theories of dual-task.

As stated at the beginning of this chapter, dual-task theories generally aim to provide an explanation for the occurring interferences in simultaneously performing two tasks. In this context, the theory of *capacity-sharing* might be the most frequently used, describing the distribution of processing capacity to existing demands. Based on the assumption that the human system has a finite amount of processing capacity, occurring interferences are attributed to this aspect (Kahneman, 1973; Navon & Gopher, 1979; Tombu & Jolicœur, 2002). While Norman and Bobrow (1975) coined this assumption with the term 'resources', previous articles described it in terms of capacity, attention, effort, etc. (Kahneman, 1973; Kerr, 1973; Moray, 1967; Navon & Gopher, 1979; Posner & Boies, 1971; Shiffrin, 1976). Regarding the amount of resources available for processing the secondary demand, the complexity of the primary task is also reported to play an important role. In this context, Navon and Gopher (1979) summarized the parameter, characteristics of a task, underlying environmental factors and characteristics of the person under the term 'subject-task parameter' and defined it as influencing the successful execution of the tasks. To gain a better understanding of the idea of a finite amount of processing capacity responsible for the occurring interferences in simultaneous task performances, numerous have been published (Allport et al., 1972; Broadbent, 1971; Kahneman, 1973, Keele, 1973; Moray, 1967; Norman & Bobrow, 1975; Posner & Boies, 1971). On the one hand, it is suggested that one mental resource is responsible for limitations in task execution (e.g. Kahneman, 1973). On the other hand, there are some pleadings for the existence of multiple resources (Allport et al., 1972; Navon & Gopher, 1979) (Figure 13).

	Number of processes that can use a processing facility at a time	
	1	>1
Number of processing facilities		
Single	Single channel (Welford, 1952)	Single capacity (Kahneman, 1973)
Multiple	Multiple channels (Allport et al., 1972)	Multiple capacity (Navon & Gopher, 1979)

Figure 13 Modified description of Navon & Gopher (1979).

Although there are different assumptions within the capacity-sharing theory, it can be noted that a simultaneous processing of different demands is commonly assumed.

In contrast to capacity-sharing theories, *bottleneck models* (e.g. Pashler & Johnston, 1989) assume that it is impossible to process two or more tasks at the same time. First described by Welford (1952) in the context of the psychological refractory period, it is assumed that a ‘bottleneck’ occurs when two tasks need a single mechanism at the same time (Pashler, 1993; Pashler, 1994). Therefore, bottleneck models suggest structural limitations rather than strategic choices (Pashler, 1994). During recent years, numerous studies have compared the two approaches of capacity-sharing and bottleneck. Within their article ‘Uncorking the Central Cognitive Bottleneck’, Schumacher et al. (2001) postulated that a perfect temporal distribution and thus a simultaneous processing in dual-task settings (within basal choice-reaction tasks) is generally possible. The authors combined auditory-verbal and visual-manual tasks and increased the difficulty due to the number of applied items as well as the extent of stimulus onset asynchrony. The results demonstrated the ability of participants to divide capacity on applied tasks. Furthermore, the fact that occurring interferences can be modulated by instructions regarding the task prioritization was highlighted. Another study recommending the theories of capacity-sharing was conducted by Tombu and Jolicœur (2002). Here, the authors combined auditory-manual and visual-manual tasks with different stimulus onset asynchrony as well as a varied order of stimuli. Differences in the performance of task one were shown with the increasing task complexity of task two. Based on their findings, the authors suggested that the allocation of capacity occurred gradually. By contrast, Ruthruff, Pashler and Hazeltine (2003) postulated a structural, central bottleneck within the simultaneous execution of two tasks.

In addition to the capacity-sharing theories and the bottleneck models, the theories of *cross-talk* should be additionally considered. Here, it is generally assumed that the amount of interferences depends on the similarity of simultaneously-performed tasks (Navon & Miller, 1987). For example, Navon and Miller (1987) showed that situations in which the distractor of one task is similar to the target category of a second task lead to higher interferences compared to situations with clear differences in the content. A more recent study conducted by Koch (2009) investigated the effects of a non-speeded visual task (different objects) and an auditory-manual reaction-time task combination. During the presentation of the objects, group one was instructed to focus on the left-right orientation of the presented object, while participants in group two were introduced to identify specific objects. In combination with the ‘high and low tone task’, the results showed higher cross-talk among the group that was instructed to focus on the left-right orientation compared to the object identification group. Based on their results, the authors suggested stronger cross-talk in compatible vs. incompatible trials.

Comparing the different theories, there is no consensus regarding what best describes humans' information processing and occurring load in performing two tasks simultaneously. To gain a further insight into the current understanding of humans' ability to perform two tasks simultaneously, the next sub-chapter will provide an overview of previous findings in both behavioral and neurophysiological settings.

2.4.1. Behavioral findings

The present sub-chapter of behavioral findings is divided into the combination of two cognitive tasks (cognitive x cognitive) and the combination of a motor and a cognitive task (cognitive x motor).

Cognitive x cognitive

Combining two cognitive tasks is commonly used in a broad variety of research questions. For example, Baddeley, Lewis, Eldridge, and Thomson (1984) and Baddeley (1996), demonstrated a reduced task performance in combining two working memory tasks. Furthermore, Phillips, Tunstall and Channon (2007) investigated the role of working memory in dynamic social cue decoding tasks. Within two experiments, the authors combined the Interpersonal Perception Task and the Profile of Non-verbal Sensitivity with the attentionally-loading 0-back task and the working memory loading 2-back task. The results demonstrated a demand on working memory only in the Profile of Non-verbal Sensitivity but not in the Interpersonal Perception Task. Furthermore, Hegarty, Shah and Miyake (2000) examined the influence of different secondary executive tasks on the performance of three psychometric visuo-spatial tasks. The results showed a decrement in performance with increasing task demand on the executive mechanism. The effects of concurrent working memory load on stroop task performance were investigated by Kim, Kim and Chun (2005). Within three experiments, the authors showed that concurrent working memory load does not always impair executive control. In this context, the content of the working memory task and the task-relevant information seem to play a highly relevant role. In a previous dual-task study, the stroop task was also used by Kahneman and Chajczyk (1983), who demonstrated a reduced stroop effect by presenting additional distractors in the display. Measuring eye movements, van Gelder, Lebedev, Liu and Tsui (1995) found an improvement of eye-tracking performance in combination with an auditory listening task, but no differences in combination with a distraction task. The results were confirmed by Kathmann, Hochrein and Uwer (1999), who showed a reduced pursuit error rate when attention was divided between two tasks. Here, the authors combined a visual-tracking task (moving target with constant or unpredictably varying velocity) with an auditory discrimination tasks. Participants in the study conducted by Karatekin et al. (2004) had to perform an auditory digit span and a simple visual response time task. Focused on both behavioral and pupillary measures, the authors reported a weak increase in task-evoked pupillary responses under the dual-task compared to the single-task condition. Additionally, an increase in reaction time was revealed in the dual-task setting. Another study that combined two cognitive demanding tasks was conducted by Shallice et al. (1985). Combining a reading and a listening task in which independent streams of random words were presented at rapid rates, the authors demonstrated only minor single- to dual-task decrements.

The effects of decision making under dual-task conditions hold specific interest for the present context. As reported in the previous chapter, studies in this context have revealed interferences in additionally using cognitively demanding (Gathmann et al., 2014a,b; Gathmann et al., 2015; Pabst, Schoofs, Pawlikowski, Brand, & Wolf, 2013b; Starcke, Pawlikowski, Wolf, Altstötter-Gleich, & Brand, 2011b; Verbruggen, Adams, & Chambers, 2012). For example, in addition to aforementioned studies, Starcke et al. (2011b) revealed less advantageous decision behavior in simultaneously performing a high executive load task (2-back) compared to single decision making. Using a secondary task that induced cautious motor responding, Verbruggen et al. (2012) demonstrated a decline in gambling behavior. Furthermore, Pabst et al. (2013b) used the Trier Social Stress Test to induce stress and asked participants to subsequently perform a decision-making task either as a single-task or in combination with a 2-back task. Stressed participants showed similar decision-making behavior under dual-task conditions than non-stressed participants under single-task conditions. Another study that used the same paradigm in combination with magnetic resonance imaging revealed no significant differences in task performance (Gathmann et al., 2014a). In contrast to the behavioral findings, neuro-imaging data showed increased activity in the anterior prefrontal cortex when stressed participants performed the 2-back task simultaneously with the decision task compared to single-task performance.

Before considering the task combination of motor and cognitive tasks, a brief excursion to the cognitive involvement in motor demands seems inevitable. Therefore, the following section summarizes findings regarding the underlying mechanisms of various motor demands as well as existing approaches.

Cognitive involvement in motor demands

Considering the role of cognitive mechanisms in motor demands, the work conducted by Hauert (1986), plays a central role. In contrast to previous theories, the author introduced the approach that motor functions represent cognitive functions (Hauert, 1986). Furthermore, Georgopoulos, Crutcher, & Schwartz (1989) disproved the assumption that the motor cortex merely represents a first motoneuron. Here, the authors suggested that the motor cortex must rather be seen as a fundamental junction in processing cognitive information, related to motor functions. To date, this assumption has been confirmed by numerous non-human (Alexander & Crutcher, 1990a; Alexander & Crutcher, 1990b; Ashe et al., 1993; Carpenter, Georgopoulos, & Pellizzer, 1999; Kettner, Marcario, & Clark-Phelps, 1996; Pellizzer, Sargent, & Georgopoulos, 1995; Riehle, Kornblum, & Requin, 1997; Shen & Alexander, 1997; Smyrnis, Taira, Ashe, & Georgopoulos, 1992; Wise, Moody, Blomstrom, & Mitz, 1998; Zhang, Riehle, Requin, & Kornblum, 1997) and human studies using electroencephalography (Beisteiner, Höllinger, Lininger, Lang, & Berthoz, 1995), magnetoencephalography (Lang, Cheyne, Höllinger, Gerschlager, & Lindinger, 1996), positron emission tomography (Honda, Deiber, Ibáñez, Pascual-Leone, Zhuang, & Hallett, 1998), functional magnetic resonance imaging (Karni et al., 1998; Lotze et al., 1999; Tagaris et al., 1998; Ungerleider, 1995) as well as transcranial magnetic stimulation (Chen, Gerloff, Hallett, & Cogen, 1997; Classen, Liepert, Wise, Hallett, & Cohen, 1998; Gerloff, Corwell, Chen, Hallett, & Cohen, 1998).

Along with the relevance of the motor cortex, numerous previous studies have reported an involvement of cortical regions in both continuous and sequential movements; for example, in grasping and holding movements (Agashe, Paek, Zhang, & Contreras-Vidal, 2015; Alahmadi et al., 2015; Gevins, Schaffer, Doyle, Cutillo, Tannehill, & Bressler, 1983; Grol et al., 2007; Park et al., 2015; Pavlova, Hedberg, Ponten, Gantelius, Valero-Cuevas, & Forssberg, 2015) as well as sequences of bimanual movements (Andres, Mima, Schulman, Dichgans, Hallett, & Gerloff, 1999; Debaere, Wenderoth, Sunaert, Van Hecke & Swinnen, 2004; Gerloff & Andres, 2002; Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003). Considering the underlying mechanisms of finger movements, Rao et al. (1993) and Salmelin, Forss, Knuutila and Hari (1995) revealed differences in cortical activity by varying the time and complexity of the movements. Similar findings were shown by Toma et al. (2002), who reported an increased activity in bilateral sensorimotor and supplementary motor area with increasing speed of motion. In the context of grasping and holding, Gevins et al. (1983) investigated the occurring differences between a move and non-move task by using electroencephalography. Considering the P300, the authors reported stronger correlations between occipital and central electrodes as well as occipital and frontal electrodes in the move compared to non-move task. In a functional magnetic resonance imaging study, conducted by Grol et al. (2007), the authors disproved the assumption of a specific cerebral conjunction for grasping objects. Furthermore, they reported an increased inter-regional coupling within the dorsomedial circuits in grasping large objects, whereas grasping small objects increased the effective connectivity of a mainly dorsolateral circuit. Regarding the recognition and correction of errors in performing movements, previous clinical studies highlighted the relevance of the posterior-parietal cortex. For example, Gréa et al. (2002) showed that patients with an injury of the posterior-parietal cortex were able to plan movements of grasping stationary objects, but were unable to correct their movements as soon as an unexpected change in the position of the object occurred. This is in accordance with previous transcranial magnetic stimulation studies (Desmurget, Epstein, Turner, Prablanc, Alexander, & Grafton, 1999). Additionally, the relevance of the posterior-parietal cortex within feedback processes of motor functions was discussed by Buneo and Andersen (2006). While participants in the study conducted by Grol et al. (2007) had to move the object after grasping, Agashe et al. (2015) asked their participants to grip different objects exclusively. Using electroencephalography, the authors showed an early involvement of contralateral fronto-central areas, followed by a later activation of central electrodes over primary sensorimotor cortical areas. Alahmadi et al. (2015) investigated the effects of five different grasping tasks (firm grasping, repeated grasping, etc.). The results demonstrated inter alia increased activity in sensory areas in more difficult tasks. Neural representation of tactile information was investigated by Pavlova et al. (2015). In their study, participants had to compress an unstable spring between the thumb and index finger under two conditions: condition one comprised the blocking of digital nerves by local anesthesia, whereas in condition two participants were asked to perform the task under ‘normal’ circumstances. Comparing the two conditions, the authors revealed a maintenance of overall activity as well as an increase in activity in the dorsal premotor cortex after blocking the nerve. Furthermore, Park et al. (2015) investigated the question concerning which motor cortical region best predicts imagined movement. Using two kinds of tasks (grasp and rotation tasks) under both real and imagined conditions, the authors revealed the most predictive information about the distinction between executed movement and imagined movement in the primary motor cortex. On the other hand, the supplementary motor area keeps the most predictive information for imagined movements. Another study in this context was conducted by Nair et al. (2003), who asked their participants to execute a ‘finger to thumb’ opposition task unimanually (left and right hand separately) and bimanually (both hands sequencing together). Participants showed an intricate network comprising the sensorimotor cortex, supplementary motor area, superior parietal lobe and cerebellum active under the execute condition. Nair et al. (2003) reported large absence of cerebellar activity under imagination. Within their review, Gerloff and Andres (2002) reported evidence of an extended cortical network involved in bimanual motor activities, which comprises the bilateral primary sensorimotor cortex (SM1), supplementary motor area, cingulate motor area, dorsal premotor cortex and posterior-parietal cortex. While grasping or holding are generally classified as ‘simple’ motor tasks, Hesse and Deubel (2011) as well as McBride, Boy, Husain and Sumner (2012) highlighted the complexity of this kind of tasks by reporting the necessity of including sensory, motor and cognitive systems for its successful performance. In this context, Georgopoulos (2000) described ‘non-cognitive’ movements as those that are not explicitly planned or instructed in their execution, such as the arm swing while walking. Thereby, walking itself must be seen as highly complex for the sensory and cognitive system (Al-Yaha, Dawes, Smith, Dennis, Howells, & Cockburn, 2011; Sheridan & Hausdorff, 2007). The involvement of higher cognitive control in walking was previously reported by numerous imaging studies in real (Harada, Miyai, Suzuki, & Kubota, 2009; Miyai et al., 2001; Suzuki et al., 2004), imagined (Bakker, De Lange, Helmich, Scheeringa, Bloem, & Toni, 2008; Iseki, Hanakawa, Shinozaki, Nankaku, & Fukuyama, 2008; Jahn, Deutschländer, Stephan, Strupp, Wiesmann, & Brandt, 2004; Malouin, Richards, Jackson, Dumas, & Doyon, 2003), and simulated walking conditions (Francis et al., 2009; Huda et al., 2008; Sahyoun, Floyer-Lea, Johansen-Berg, & Matthews, 2004). Based on the present excursion, occurring interferences in simultaneously performing a cognitive and a motor task become more understandable, as will be shown in the next sub-chapter.

Cognitive x motor

Within an early study, Abernethy (1988) postulated that dual-task paradigms additionally enable the quantification of the relative cognitive demand of motor functions. The present chapter sheds light on both primary and secondary task-performance in dual-task studies that implemented gait or postural control. Combining memory tasks with sitting and tandem stance, Kerr, Condon and McDonald (1985) demonstrated a decrease in spatial but not non-spatial memory task-performance under the tandem stance condition. Furthermore, balance was not interrupted by the spatial nor the non-spatial task. By contrast, Dault, Frank and Allard (2001a) reported a decrease in postural sway during different working memory tasks, regardless of the task type or difficulty. The authors confirmed their results in a second study, in which both standing and cognitive task difficulty were varied (Dault, Geurts, Mulder, & Duysens, 2001b). Participants in the study conducted by Ramenzoni, Riley, Shockley and Chiu (2007) performed three different working memory tasks while standing bipedal. The results showed a reduced postural sway variability during rehearsal and increased variability during encoding. Using a spatial and non-spatial memory task, Maylor, Allison and Wing (2001) reported only marginal effects in cognitive task performance while standing compared to sitting. Furthermore, Mitra (2003) asked their participants to stand feet closed and simultaneously perform a conjunction search task. The results showed a faster performance of the cognitive task in closed stance compared to normal standing (feet at a comfortable angle). Aiming to provide a better understanding of improving balance performance, by using additional cognitive tasks, Swan, Otani, Loubert, Sheffert and Dunbar (2004) asked their participants to perform spatial and non-spatial memory tasks (similar to Kerr et al., 1985) under the following four sensory conditions: eyes open with force plate fixed, eyes closed with force plate fixed, eyes open with force plate sway-referenced, and eyes closed with force plate sway-referenced. The results demonstrated a decrease in postural sway in the most difficult balancing task while simultaneously performing a memory task in both spatial and non-spatial memory conditions.

In order to increase the difficulty of motor demands, other studies have used perturbation or dynamic platforms. For example, Shumway-Cook and Woollacott (2000) applied six different sensory conditions from a firm surface with eyes open to a sway-referenced surface, optokinetic stimulation. In combination with a choice-reaction time auditory task, young participants showed no effects in any of the sensory conditions while additionally performing the secondary task. The work conducted by Riley, Baker, Schmit and Weaver (2005) holds particular interest to the present context. Here, the authors applied a short-term memory task both visually and auditory while participants stood on a rigid or compliant surface. The results showed that the spatiotemporal profile of postural sway was affected by both conditions, but to a greater degree by the auditory one. No differences between visual and auditory were reported by Hunter and Hoffman (2001), but a greater variability of the center of pressure in the non-cognitive condition. In the study conducted by Vuillerme, Nougier and Teasdale (2000), participants were asked to verbally responsd to visual and auditory stimuli while standing on a force platform. The results indicated a reduced displacement of the center of pressure while concurrently performing a reaction-time task. Furthermore, there was no effect of the difficulty of the task, nor any differences between the types of stimuli. The effect of articulation under dual-task circumstances has been investigated by Yardley, Gardner, Leadbetter and Lavie (1999) and Dault, Yardley and Frank (2003). Both studies combined a spoken mental task with different postural demands. Focusing on articulation and attention, Yardley et al. (1999) found a significant increase in sway based on articulation, whereas no effect of attention was observed (in the unstable surface condition). Similar was reported by Dault et al. (2003). Along with a general increase of sway frequency and decrease of sway amplitude under dual-task conditions, articulation resulted in a more pronounced increase of sway compared to non-articulation tasks. The influence of attention on the dynamical structure of postural sway was further examined by Donker, Roerdink, Greven and Beek (2007). The authors asked their partici pants to stand upright with eyes open, eyes closed, eyes open while performing a cognitive task and eyes closed while performing a cognitive task. The results showed that standing with eyes closed leads to a significant increase of the center of pressure regularity. Furthermore, performing an additional cognitive task while standing with eyes closed leads to greater irregularity and lesser variability. Four conditions of varied attentional demands were used by Pellecchia (2003). While standing on a compliant surface, participants proved to be mostly influenced by the most difficult cognitive task, although the additional performance of all cognitive tasks resulted in differences of postural control. In the study conducted by Siu and Woollacott (2007), participants stood with feet together and were asked to prioritize the standing task or an additionally-performed visual spatial memory task. The authors demonstrated effects of prioritization in the cognitive but not in the postural control task. The influence of different instructions on simultaneously performing a motor and cognitive task was investigated by Mitra and Fraizer (2004). While most previous studies asked to focus on either a minimization of their sway or to take up stance and perform the cognitive task, Mitra and Fraizer (2004) additionally used the instruction of focusing on both tasks equally. Along with an increased error rate with increasing cognitive demand, participants performed the cognitive task faster under search-only instructions, which reversed significantly under combined instructions.

Along with postural control studies, gait is a commonly-used motor component in dual-task settings. Focusing on both standing and walking, Lajoie, Teasdale, Bard and Fleury (1993) reported significantly greater attentional cost for walking than standing under dual-task conditions. Furthermore, reaction time increased in the single-support phase compared to the double-support phase. Similar findings were reported by Ebersbach, Dimitrijevic and Poewe (1995), who investigated the effects of simultaneously performing a memory-retention task and a fine motor task on walking performance. Here, Ebersbach et al. (1995) reported an increase in double-support time in additionally performing a memory-retention task as well as a fine motor task. Furthermore, the authors found a decrease in cognitive task performance during gait. In the study conducted by Woollacott and Shumway-Cook (2002), participants were asked to walk a 10-meter conductive walkway under single-task and four dual-task conditions. However, finger tapping was the only secondary task that produced a significant decrease in stride time, whereas double-support time was significantly affected by both fine motor tasks and memory tasks. Furthermore, a greater reduction in recall performance of the digit span task was reported for gait compared to a quiet stance. Considering the variation of walking speed, Dennis et al. (2009) demonstrated a higher error rate in the cognitive task with increased walking speed. While Dubost, Annweiler, Aminian, Najafi, Herrmann and Beauchet (2008) reported no effects of a verbal fluency task on stride velocity, Beauchet, Dubost, Herrmann and Kressig (2005a) demonstrated a decline in gait speed and the ability to enumerate numbers in an arithmetic task while walking. Combining different cognitive tasks with sitting, walking with preferred speed and walking under slow speed conditions, Patel, Lamar and Bhatt (2014) reported the lowest motor cost in the visuo-motor task and the highest for the stroop task under walking with a preferred speed. Considering the cognitive task-performance, the cost was highest for the visuo-motor task and lowest for the stroop task. Walking with slow speed resulted in increased motor cost and reduced cognitive cost only for the stroop task. Similar to the postural control study conducted by Mitra and Fraizer (2004), Kelly, Eusterbrock and Shumway-Cook (2013) again focused on different instructions. In walking under simple usual-base conditions with the instructions of equal focus and cognitive focus, participants showed no differences, whereas the instructions of walking focus and cognitive task prioritization resulted in different task performance. In the narrow base walking, the authors reported similar findings for the equal-focus and walking-focus instructions, but differences for the cognitive-focus instructions. Based on their findings, Kelly et al. (2013) highlighted the dynamic and flexible character of task prioritization.

2.4.2. Neurophysiological findings

The present chapter reviews literature investigating the underlying structures of performing two tasks simultaneously, independent of the kind of tasks. Principally, the findings can be classified based on the following pattern: 1) increased activity under dual- compared to single-task conditions; 2) no differences in the activity of the underlying structures; and 3) decreased activity in dual- compared to single-task conditions (Figure 14).

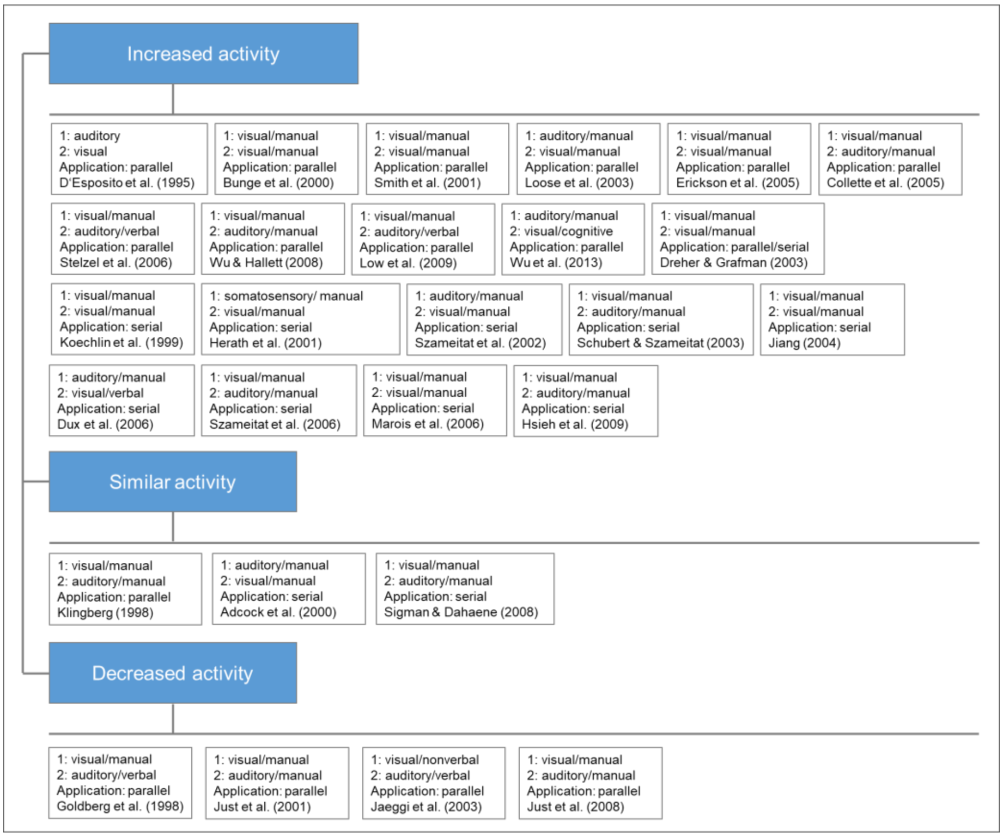


Figure 14 Previous findings of dual-task related neural activity.

Studies reporting *similar* activity in single- compared to dual-task conditions consistently combined an auditory and a visual task. Here, Klingberg (1998) used two different working memory tasks, whereas Adcock, Constable, Gore and Goldman-Rakic (2000) combined an auditory noun task and a visual space or face task. Furthermore, Sigman and Dahaene (2008) combined different tones (auditory) and numbers (visually) with an inter-stimulus interval of 300ms. Considering studies reporting a *decrease* of neuronal activity in dual- compared to single-task conditions, both a specific (Goldberg et al., 1998; Just, Carpenter, Keller, Emery, Zajac, & Thulborn, 2001; Just, Keller, & Cynkar, 2008) as well as a general (Jaeggi et al., 2003) decrease have been reported.

The category of *increased* activity in dual- compared to single-task conditions comprises 20 studies with different task settings. While some of these studies compared single- and dual-task conditions, others investigated only the dual-task condition itself. Nevertheless, I assume that summarizing all structures reported to show increased activity under dual-task conditions might manifest a common pattern in dual-task performance (Figure 15).

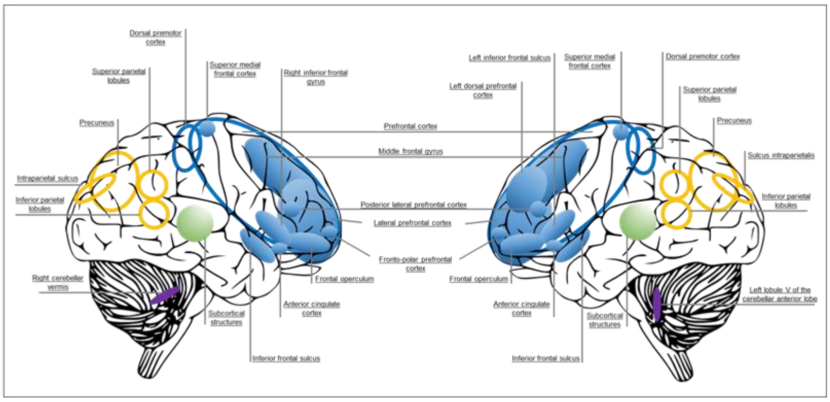


Figure 15 Underlying structures of dual-task.

Considering the underlying mechanisms, a large variance of the activated structures becomes apparent. This might not be surprising because the dual-task paradigm does not comprise two clearly-defined tasks. However, more importantly there is no cortical structure, commonly active in dual-task situation, although the prefrontal cortex has been shown to be activated dominantly.

Considering the investigated tasks within the reviewed studies, most researchers have concentrated on the combination of two cognitive tasks, whereas only small evidence comes from the additional performance of a motor task. The two studies that included a motor component combined self-paced tapping and a visual letter-counting task. Using functional magnetic resonance imaging, Wu, Liu, Hallett, Zheng and Chan (2013) identified increased activity in the precuneus and the cerebellum under dual-task conditions, whereas Wu and Hallet (2008) reported an additional activity only in structures of the precuneus. Herath et al. (2001) investigated dual-task related activity by using a somatosensory task. Here, the authors applied blunt, painless stimuli, while participants had to respond manually by pressing a button. The serial performance (stimulus onset asynchrony ranging from 200-1200ms) with an additional cognitive task (application of different lights) resulted in increased activity in the right inferior frontal gyrus only under small stimulus onset asynchrony conditions. Jiang (2004) combined two cognitive tasks with a manual response. In accordance with Herath et al. (2001), the authors reported increased activity in the right inferior frontal gyrus only under small stimulus onset asynchrony. Furthermore, the author reported increased activity in the frontal operculum. While Jiang (2004) and Herath et al. (2001) showed a right handed increase of activity in the inferior frontal gyrus, both Marois et al. (2006) and Hsieh et al. (2009) revealed a bilateral increase in the inferior frontal gyrus. In addition, Marois et al. (2006) found increased activity in the dorsal premotor cortex, whereas Hsieh et al. (2009) identified a dual-task related increase of activity in the following structures: anterior insula, orbitofrontal cortex, lateral prefrontal cortex, supplementary motor cortex, anterior and posterior cingulate gyrus, right superior parietal lobe, right intraparietal sulcus, right precuneus and right cuneus. In their study, participants had to watch a video of driving a car while answering different questions. Furthermore, they combined the conversation task with the additional presentation of red circles or ring tones (answering manually). The relevance of the frontal lobe in dual-task situations was additionally confirmed by Erickson et al. (2005), who identified increased activity in the anterior cingulate cortex and the prefrontal cortex. Furthermore, the authors reported increased activity in the parietal lobe (inferior parietal lobe and superior parietal lobe) as well as subcortical areas under dual-task conditions. Increased activity in the prefrontal cortex was also reported by D'Esposito, Detre, Alsop, Shin, Atlas and Grossman (1995). In their study, the authors combined a verbal and a spatial passive working memory task. Increased activity in the left prefrontal cortex was shown by Bunge et al. (2000) and Loose, Kaufmann, Auer and Lange (2003). While Bunge et al. (2000) used a paradigm consisted of two working memory tasks, Loose et al. (2003) combined different tones (frequency of 450 and 1070 Hz) and different symbols (circles and crosses). Along with these findings, numerous studies have reported a dual-task related increase of activity in specific structures within the prefrontal cortex (Dux et al., 2006; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999; Smith, Geva, Jonides, Miller, Reuter-Lorenz, & Koeppe, 2001; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006). For example, Dux et al. (2006) demonstrated increased activity in the posterior lateral prefrontal cortex as well as the superior medial frontal cortex, which is reported as highly relevant in both motor and cognitive control (Nachev, Kennard, & Husain, 2008; Picard & Strick, 2001; Rushworth, Walton, Kennerley, & Bannerman, 2004). The authors used a serial presentation (SOA: 300, 1100, and 1900ms) of eight different tones and eight circles with different colors. While people had to respond manually in the auditory task, they gave their answer verbally in the visual task (Dux et al., 2006). Analyzing an online letter-matching task under four conditions - control, delay, dual-task and branching - Koechlin et al. (1999) suggested that the fronto-polar prefrontal cortex selectively mediates humans' ability to hold a primary goal in mind, while exploring and processing a secondary goal. Smith et al. (2001) reported a dual-task related increase in left dorsolateral prefrontal cortex activity, albeit only among younger adults. In their study, participants had to evaluate words or equations in terms of, whether they are right or wrong. In addition, a memory task was simultaneously presented, in which participants had to memorize words and recite them later. Increased activity in the lateral prefrontal cortex was reported by Szameitat et al. (2006), who explained their results with the temporal coordination of the dual-task performance. Furthermore, Szameitat et al. (2006) identified a specific increase in right frontal gyrus activity, which was already reported by Herath et al.

(2001), Jiang (2004) and Marois et al. (2006). A third structure identified by the authors comprises the left inferior frontal sulcus. This was also reported by Schubert and Szameitat, (2003) and Collette et al. (2005) (bilateral). In this context, Schubert and Szameitat (2003) suggested the left inferior frontal sulcus as a key structure in performing dual-task. Furthermore, Collette et al. (2005) described a dual-task related increase in anterior prefrontal cortex as well as posterior middle frontal gyrus activity. Considering the characteristic of the tasks, both studies combined a visual and an auditory task but differed in the way of presentation: while Schubert and Szameitat (2003) presented the stimuli in a serial way (SOA: 125 and 200ms), Collette et al. (2005) presented the stimuli simultaneously. Szameitat et al. (2002) and Low, Leaver, Kramer, Fabiani and Gratton (2005), identified increased activity in the posterior middle frontal cortex. While Szameitat et al. (2002) used functional magnetic resonance imaging; Low et al. (2009) used an event-related optical signal. Combining a visual and auditory task, participants in the study of Szameitat et al. (2002) had to react directly to a stimulus, whereas those in the study of Low et al. (2009) had to count specific tones and reflect them at the end. In the visual task, Szameitat et al. (2002) presented quadrates with different colors, while Low et al. (2009) used series of letters. Furthermore, Low et al. (2009) presented the stimuli in a simultaneous way, whereas Szameitat et al. (2002) combined the stimuli with a stimulus onset asynchrony of 50, 125 and 200ms. Along with the increased posterior middle frontal gyrus activity, Szameitat et al. (2002) identified increased activity in the inferior frontal sulcus and the intra-parietal sulcus. Regarding the dual-task related increase in inferior frontal sulcus, the findings are in accordance with Stelzel, Schumacher, Schubert and Mark (2006). Here, the dual-task paradigm comprised a visual (localization of signals) and an auditory task setting (distinguishing between tones with different frequency), where participants had to response either manually or verbally.

While most of the reported studies combined a visual and an auditory task, Dreher and Grafman (2003) used only visual task combinations. In their study, participants had to decide whether the presented letter is a vowel or a consonant, as well as further determining the location of its presentation. The results indicated increased activity in the anterior cingulate cortex in performing two tasks simultaneously. Furthermore, the lateral prefrontal cortex as well as the intra-parietal sulcus region showed increased activity under task-switching conditions. Additionally, Szameitat et al. (2006) described increased activity in the lateral prefrontal cortex in a visual / visual dual-task setting, Here, the stimuli were presented with a stimulus onset asynchrony of 200ms. Among the studies, reporting increased activity in dual- compared to single-task conditions, all studies except Wu et al. (2013) and Wu and Hallet (2008), who reported increased activity in frontal structures.

Therefore, it can be assumed that the frontal lobe plays a significant role in dual-task performance, independent of the type of stimulus, kind of response, way of presentation or temporal combination (either with or without a delay).

2.4.3. Age-related differences in dual-task performance

During the previous sub-chapters, it became apparent that the amount of interferences in simultaneously performing two or even more tasks depends on numerous factors. One aspect frequently discussed in the past address the effects of aging. (Beurskens & Bock, 2012; Riby, Perfect, & Stollery, 2004; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). In general, there is inconsistency concerning whether the process of aging is associated with increased dual-task costs (e.g. Baddeley, Baddeley, Bucks, & Wilcock, 2001b; Logie et al., 2004; Nyberg, Nilsson, Olofsson, & Bäckman, 1997). One explanation for this inconsistency comes from Riby et al. (2004), who suggested that the methodological variation in dual-task studies is responsible for the phenomenon. Furthermore, the characterization of simultaneously-performed tasks - as supposed by Lindenberger, Marsiske, & Baltes (2000) - seems to play a highly relevant role. In this context, Verhaeghen and Basak (2005) highlighted simple and choice-reaction time tasks, working memory tasks, tests of episodic memory, tests of spatial and reasoning abilities, mental rotation, and visual search performance as being sensitive to measuring age-related differences.

Findings have supported the idea of increased age-related dual-task cost with increasing task difficulty / complexity, summarized in the complexity hypothesis (e.g. Hartley & Little, 1999; Mattay et al., 2002; McDowd & Craik, 1988; Salthouse, Rogan, & Prill, 1984; Wright, 1981). On the other hand, studies have proposed greater age-related differences in performing simple tasks (Crossley & Hiscock, 1992; Korteling, 1991). In contrast to the assumption of a mediation of task difficulty / complexity on age-related dual-task costs, in their meta-analysis Verhaeghen et al. (2003) suggested an independency of these variables. Focusing on age-related differences of dual-task costs in simultaneously performing two cognitive tasks, Jennings, Brock and Nebes (1990) combined an arithmetic task with an additional monitoring task. The authors reported that older participants were less well prepared for rapidly presented stimuli compared to younger participants. Interesting findings in the context of task difficulty / complexity come from Vaportzis, Georgiou-Karistianis and Stout (2013), who combined simple and complex reaction-time tasks with digit tasks. The results indicated that older adults performed significantly slower, but as accurately as younger adults in the simple choice-reaction time task, whereas a reversed pattern was shown in the more complex choice response time task. Here, older adults were significantly less accurate, but as fast as younger adults. Based on their findings, the authors suggested different age-related strategies depending on complexity and difficulty. Different modalities in stimulus presentation were focused in an early study by Baron and Mattila (1989). Here, both groups reported a decrease under dual-task compared to single-task conditions, but older participants performed much worse under single- and dual-task. Another early study combining the two modalities of auditory and visual presentation, was introduced by McDowd and Craik (1988). In order to additionally manipulate task difficulty, the authors created four different task combinations from a simple / simple to a difficult / difficult task combination. The results showed a general age-related slowing, as well as a further deterioration under the most difficult dual-task condition, as assumed in the complexity hypothesis. Switching rapidly between an auditory and a visual task, Hawkins, Kramer and Capaldi (1992) reported greater dual-task cost among older adults compared to younger adults. Task switching was also investigated by Kray and Lindenberger (2000) in a sample size of 118 adults aged from 20 to 80 years. Based on their findings of significantly greater age-related increments in general vs. specific switch costs, the authors suggested that the coordination of two alternating task sets is more negatively affected during the process of aging than the switching itself. Using a semantic and an episodic dual-task paradigm, Riby et al. (2004) reported age-related differences only in episodic but not in semantic dual-task paradigms. Kemper, Schmalzried, Herman, Leedahl and Mohankumar (2009) used a digital pursuit rotor task, whereby young adults experienced greater dual-task costs to tracking, fluency and grammatical complexity than older adults. Furthermore, older adults were able to preserve their tracking performance by speaking more slowly. Again, the results indicated that the strategies used in executing dual-task situations differ between younger and older adults. While numerous findings of age-related differences in dual-task performance are based on the combination of two cognitive tasks, many more have focused on the simultaneous performance of motor and cognitive tasks. This may be caused by the increasing risk of falling / accidents among older adults in performing a motor and a cognitive task simultaneously (e.g. Beauchet, Dubost, Herrmann, Rabilloud, Gonthier, & Kressig, 2005b; Kressig, Herrmann, Grandjean, Michel, & Beauchet, 2008; Lundin-Olsson et al., 1997; Verghese et al., 2002). Within their review, Schaefer and Schumacher (2011) reported greater dual-task decrements in the elderly in both cognitive and motor tasks. Furthermore, the authors reported a task prioritization of motor compared to cognitive tasks. Aiming to gain a better understanding of both age and task effects in simultaneously performing cognitive and motor tasks, Srygley, Mirelman, Herman, Giladi and Hausdorff (2009) combined three different cognitive tasks with a sitting and walking condition. In contrast to the hypothesis that older adults prioritize the performance of motor tasks compared to cognitive tasks, the authors found an age-related decline in walking performance while simultaneously performing 3 and 7 subtractions as well as phoneme monitoring, whereas content recall enhanced. An age-related increase in the dual-task cost of both domains was previously reported by Lindenberger et al. (2000). In their study, 47 young (aged 20-30 years), 45 middle-aged (aged 40-50 years) and 48 old (aged 60-70 years) participants encoded word lists while sitting, standing, or walking on two narrow tracks with different path complexity. A decline in both domains was also reported by Sparrow, Begg and Parker (2006). In their study, participants had to walk with their preferred walking speed and simultaneously perform a reaction-time task. While reaction time decreased in both groups under dual-task conditions, younger people showed a significantly faster walking speed under single- and dual-task conditions. Along with reaction-time tasks, numerous studies have investigated the effects of performing memory tasks while executing different motor tasks. In this context, Li, Lindenberger, Freund and Baltes (2001) asked their participants to perform a memory task while simply walking or completing an obstacle course. With increasing difficulty of the walking task (obstacle course) older adults’ memory performance declined, which is in accordance with the already-stated assumption of a task prioritization. Focusing on the effects of additionally performing a working memory task, Lövdén, Schaefer, Pohlmeyer and Lindenberger (2008) combined different n-back tasks with simultaneous treadmill walking. While both groups reported lower stride-to-stride variability in dual- compared to single-task conditions, stride time and length variability decreased with the increasing difficulty of the working memory task among younger but not among older participants. Based on the general assumption that walking while talking adversely affects gait performance and increases the risk of falling among the elderly, Plummer D’Amato, Altmann and Reilly (2011) combined a spontaneous speech task as well as an auditory stroop task with normal walking. Under the dual-task condition, older people showed a significant decrease in walking performance under both cognitive tasks. A previous study conducted by Siu, Lugade, Chou, van Donkelaar and Woollacott (2008) also used an auditory stroop test, although rather than simply involving walking conditions, participants had to complete an obstacle course. Focusing on both domains, cognitive attention in the stroop task diminished in all participants under dual- compared to single-task conditions, whereas gait performance declined only among the older group. No age-related effects were found by Springer et al. (2006), who combined normal walking with three different cognitive tasks (listening to and remembering a simple text, listening to and remembering a complex text and serial subtracting of 7). In order to investigate spatial navigation, some studies have used virtual environments in the context of age-related differences of dual-task walking. For example, Lövdén, Schellenbach, Grossman-Hutter, Krüger and Lindenberger (2005) asked their participants to navigate through a virtual museum with and without using a handrail. Older adults reported reduced path-finding performance, as well as increased body sway while walking under cognitive load compared to single walking. Furthermore, navigation increased among older participants by using the handrail. Another virtual reality study was conducted by Neider, Gaspar, McCarley, Crowell, Kaczmarski and Kramer (2011). In their study, participants had to cross simulated streets of varying difficulty either undistracted, simultaneously listening to music or simultaneously conversing on a cell phone. Increasing the difficulty of the crossing task led to an increase in dual-task impairments among older adults but not among the younger ones. Furthermore, older adults took longer to initiate their crossing, and showed more problems in completing the street crossing while using a cell phone compared to listening to the music.

Normal standing is a seemingly effortless task for younger adults but also detrimentally affected in older adults when combined with a secondary task (e.g. Brauer, Woollacott, & Shumway-Cook, 2001; Brown et al., 1999; Shumway-Cook & Woollacott, 2000). One aspect frequently investigated in this context is the effect of simultaneously performing working memory tasks. For example, Doumas, Smolders and Krampe (2008) combined an n-back task with three different postural control tasks. Based on their findings, the authors suggested a development in resource allocation with increasing age to compensate declines in sensorimotor and cognitive processes. Combining a dynamic postural control task and a n-back task, Doumas, Rapp and Krampe (2009) showed greater dual-task costs in both tasks among older adults and higher costs in the memory component among younger adults. Another study using an additional working memory task was conducted by Rapp, Krampe and Baltes (2006). The authors indicated that older adults maintained a high level of functioning in postural control, whereas working memory task performance decreased. In accordance with Fuller (2000), these two studies again highlighted the relevance of task prioritization among older adults. Along with two different 2-back working memory tasks, Huxhold, Schmiedek and Lindenberger (2006) additionally combined a two-choice reaction time task with sitting (single-task) and standing (dual-task). The authors indicated an increased center of pressure displacement among older adults with increasing cognitive task difficulty under dual-task conditions, compared to younger controls. In their review, Woollacott and Shumway-Cook (2002) highlighted the relevance of increasing attentional resources for maintaining both postural control and gait among older adults. Attentional requirements for postural control and walking were also focused in an experimental paradigm by Lajoie, Teasdale, Bard and Fleury (1996). A relatively small sample size of eight young and eight older participants performed a verbal response task while sitting, standing, and walking. Both age groups showed a decline in reaction times as well as a decrease in walking speed. Furthermore, Hauer, Pfisterer, Weber, Wezler, Kliegel and Oster (2003) suggested that reduced dual-task performance in people with cognitive impairments is caused by a decline in attentional resources.

In addition to walking and postural control, ample evidence comes from the field of fine motor tasks, which should also be considered in this context. For example, Crossley and Hiscock (1992) combined a simple tapping task with a concurrent cognitive load. Within three age groups, older adults showed larger decrements compared to younger and middle-aged adults. Similarly, Kemper, Herman and Lian (2003) reported an age-related decline in combining finger tapping with a speech production task. Within two experiments, Fraser, Li and Penhune (2010) asked their participants to execute a sequential tapping task while simultaneously performing a semantic judgment task (experiment 1) and a mental arithmetic task (experiment 2). Under easier conditions, older adults showed a decrease in speed and accuracy of sequential tapping compared to younger adults, whereas age-related differences in the more difficult conditions were only found in the accuracy of dual-task performance.

For a further understanding of age-related differences in dual-task performance, the present subchapter ends with a brief review of studies, focusing on neurophysiological mechanisms. On the one hand, studies have reported increased activity in the prefrontal cortex of older adults (Harada et al., 2009; Heuninckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005; Heuninckx, Wenderoth, & Swinnen, 2008). On the other hand, findings have indicated an age-related decline in frontal (Park & Reuter-Lorenz, 2009; Raz et al., 2005), and especially prefrontal activity (Gunning-Dixon & Raz, 2003; Raz et al.,1997; West, 1996). By contrast, van Impe, Coxon, Goble, Wenderoth and Swinnen (2011) revealed an age-related increase in BOLD responses of a fronto-parietal network under single-, but not under dual-task conditions. Beurskens, Helmich, Rein and Bock (2014) again highlighed the relevance of the kind of tasks. In their study, participants were asked to walk on a treadmill while completing either visual or verbal-memory demands. Using functional Near-Infrared-Spectroscopy, the authors reported a decrease in prefrontal activity among the elderly, albeit only in the visual but not in the verbal-memory condition. Explaining the inconsistency of age-related over and under activity, Reuter-Lorenz and Lustig (2005) interpreted underactivity as circuitry dysfunction, region-specific atrophy or poor strategy use, thus being categorized as impairment, whereas overactivity is assumed to act as both compensation and impairment.

The present chapter has shed light on humans' ability to simultaneously perform two or even more tasks, from different perspectives. I started by highlighting the most common theories. Here, capacity sharing theories suggest a possibility of sharing processing capacity among tasks, whereas bottleneck theories discuss the impossibility of parallel processing. Additionally, cross-talk theories - which state a dependency of interferences and the content of combined tasks - were described. Within the chapter of behavioral findings, cognitive x cognitive task combinations and cognitive x motor task combinations were discussed. While most studies have reported a decline in dual- compared to single-task performance, some have highlighted a facilitation of primary task performance in facing participants with a secondary task. Supplementing the behavioral findings with neurophysiological insights, three different patterns became apparent: increased activity, decreased activity and no differences. Predominantly reporting increased activity, the activity in the underlying structures showed a high inconsistency with a common activity in the prefrontal cortex. During the sub-chapters, it became obvious that the amount of interferences in dual-task situations depends on numerous factors but is adversely affected by the process of aging. Here, findings have demonstrated differences in activity in the underlying mechanisms, but - more relevant for this group of people - a decline in performing dual-task situations.

Thus far, the chapters of executive functions, decision making, and dual-task have additionally highlighted the underlying mechanisms by focusing on studies with functional Magnetic Resonance Imaging or Positron Emission Tomography, respectively. Given that the first experiment mainly focused on electroencephalographic data, this topic will be considered in further detail during the next and last chapter.

2.5. Electroencephalography

Hans Berger first recorded electrical activity from the human scalp in 1924. This progress was based on the findings of brain electrical activity by Caton, who presented his findings at the 43rd Annual Meeting of the British Medical Association in 1875. Since its development, the electroencephalogram has become a widely-used tool in numerous fields of interest, such as sleep (Armitage & Hoffmann, 2001), language (Weiss & Mueller, 2003), memory (Klimesch, 1999), attention (Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998), and lesions (Wyllie et al., 2007).

Normal waveforms of the electroencephalogram (like many others) are described by their frequency, amplitude and location (Stern & Engel, 2004). While Berger's observations revealed the basic rhythms of alpha and beta (Berger, 1929; Rösler, 1986 for review), today five rhythms are traditionally used to classify the electroencephalogram (alpha, beta, theta, gamma, and delta) and can be described as follows:

- Gamma (35 Hz upwards)
- Beta (13 - 35 Hz)
- Alpha (8 - 13 Hz)
- Theta (4 - 8 Hz)
- Delta (1 - 4 Hz)

The alpha rhythm - also known as the Berger rhythm - is most commonly investigated. Traditionally described as 'idling rhythm' and emphasized in the 8-13 Hz band, the rhythm is focused in cognitive (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005; Klimesch, Doppelmayr, Schimke, & Pachinger, 1996; Klimesch, Schimke, & Pfurtscheller, 1993), sensorimotor (Baumeister, Reinecke, Liesen, & Weiss, 2008; Bazanova, Mernaya, & Shtark, 2009; Sauseng, Klimesch, Gerloff, & Hummel, 2009), psycho-emotional (Aftanas & Golosheikin, 2003; Cacioppo, 2004) and physiological topics (Cooray, Nilsson, Wahlin, Laukka, Brismar, & Brismar, 2011; Kiyatkin, 2010; Kiyatkin & Lenoir, 2011) (Bazanova & Vernon, 2014, for review). The term 'idling rhythm' is based on the findings of blocked alpha activity by opening the eyes (Schürmann & Başar, 2001), as well as increased alpha power in 8-12 Hz in posterior electrodes when eyes are closed (Treder, Bahramisharif, Schmidt, Van Gerven, & Blankertz, 2011) and in 9-11 Hz (Niedermeyer, 2004) / 11-13 Hz (Sterman & Egner, 2006) when limbs are at rest (Bazanova & Vernon, 2014). By contrast, other studies have described the alpha rhythm as reflecting the possible active inhibition of task-irrelevant brain circuits, rather than simple 'idling' (Busch & Herrmann, 2003; Cooper, Croft, Dominey, Burgess, & Gruzelier, 2003; Herrmann, Senkowski, & Röttger, 2004; Jensen, Gelfand, Kounios, & Lisman, 2002; Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999; Klimesch, Doppelmayr, Roehm, Pöllhuber, & Stadler, 2000; Klimesch, Sauseng, & Hanslmayr, 2007; Sauseng et al., 2005). While numerous previous studies have reported the phenomenon of visual-induced alpha blocking or alpha desynchronization primarily seen over the parieto-occipital cortex (Barry, Clarke, Johnstone, Magee, & Rushby, 2007; Klimesch, 1997), comparable results have been observed in the somatosensory system, by movements or tactile stimuli (called mu rhythm) (Chatrian 1976; Chatrian, Petersen & Lazarte, 1959; Kuhlman, 1978; Niedermeyer, 1993; Pfurtscheller, Neuper, Andrew, & Edlinger, 1997) and in the auditory system by acoustic stimuli (Niedermeyer, 1993; Tiihonen, Hari, Kajola, Karhu, Ahlfors, & Tissari, 1991). Within cognitive processes the alpha rhythm plays an important role in a variety of cognitive processes, including memory (Başar, 2004; Doppelmayr, Klimesch, Hödlmoser, Sauseng, & Gruber, 2005; Klimesch et al., 1993; Klimesch, 1996; Klimesch, Doppelmayr, Pachinger, & Ripper, 1997), attention and perception (Başar, 2004; Cooper et al., 2003; Ray & Cole, 1985), intelligence (Başar, 2006; Doppelmayr et al., 2005; Jaušovec & Jaušovec, 2000) and information processing (Bornkessel, Fiebach, Friederici, & Schlesewsky, 2004; Klimesch et al., 1993). Considering the process of memorization, Klimesch (1996) and Başar, Başar-Eroğlu, Röschke and Schütt (1989) reported a strong correlation between alpha activity and working memory. A working memory task was also used by Jensen et al. (2002), who demonstrated a linear increase of alpha activity with increasing memory load. The results reported by Sauseng et al. (2005) provide evidence of increasing alpha power at prefrontal but decreasing power at occipital electrodes during the performance of a working memory task. The authors suggested that the results should not be interpreted in terms of ‘idling’ or ‘global’ inhibition, but they may reveal a tight functional coupling between prefrontal cortical areas (Sauseng et al., 2005). On the one hand, Klimesch et al. (1999) interpreted increased alpha amplitudes during a highly-demanding working memory task in terms of the active inhibition of neural circuits subserving long-term memory. On the other hand, Klimesch (1999) emphasized that upper alpha oscillations in thalamo-cortical feedback loops reflect search and retrieval processes in (semantic) long-term memory. Furthermore, the author reported significantly higher alpha frequency in good memory performers compared to bad performers. Along with working memory and in contrast to early findings (e.g. Oswald & Roth, 1974; Vogel, Broverman, & Klaiber, 1968), subsequent studies reported evidence of a relation between alpha rhythm and the general level of intelligence (Anokhin & Vogel, 1996; Başar, 2006; Doppelmayr et al., 2005; Giannitraoani, 1985; Juolasmaa, Toivakka, Outakoski, Sotaniemi, Tienari, & Hirvenoja, 1986. Neubauer, Freudenthaler, & Pfurtscheller, 1995). While Gasser, Von Lucadou-Müller, Verleger and Bächer (1983) found a positive correlation between alpha rhythm and intelligence only among a group of mildly-retarded children, but not among a group of healthy children, Giannitraoani (1985) reported a correlation between alpha rhythm and full scale QI among a sample of normal 11 to 13 year-old children. In addition to Juolasmaa et al. (1986) - who reported correlations mainly with verbal and memory subtests of intelligence test scores - Anokhin and Vogel (1996) found correlations with alpha activity and Raven's Standard Progressive Matrices as well as verbal abilities factors derived from the verbal subtests of Amthauer's Intelligence Structure Test (IST) and Horn's LPS test of mental performance. Furthermore, Doppelmayr et al. (2005) reported a significantly larger upper alpha desynchronization in more intelligent compared to less intelligent subjects. Correlations with alpha rhythm are also frequently described in the field of attention (Busch, Duois, & VanRullen, 2009; Busch & Herrmann, 2003; Gola, Magnuski, Szumska, & Wróbel, 2013; Grimault, Robitaille, Grova, Lina, Dubarry, & Jolicœur, 2009; Händel, Haarmeier, & Jensen, 2011; Haenschel et al., 2009; Jokisch & Jensen, 2007; Leiberg, Lutzenberger, & Kaiser, 2006; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009; Ray & Cole, 1985; VanRullen, Busch, Drewes, & Dubois, 2011). For example, Händel et al. (2011) showed a higher contralateral alpha power to the unattended side, compared to the attended side. In addition, a highly interested point is listed in the review conducted by Ward (2003). While the author separated attention as being closely related to alpha and gamma rhythms, and memory to theta and gamma rhythms, previous fundamental findings suggested that the processes of memory and attention are inseparable (Baddeley, 1996; Başar & Güntekin, 2012; Desimone, 1996; Fuster, 1995; Fuster, 1997; Goldman-Rakic, 1996). Regarding the process of aging, an increasing alpha peak was revealed from childhood to early adulthood (Bazanova, 2008; Niedermeyer & da Silva, 2005; Stroganova, Orekhova, & Posikera, 1999), whereas a decrease was indicated after the age of 40 years (Bazanova & Vernon 2014; Clark et al., 2004; Köpruner, Pfurtscheller, & Auer, 1984; Osaka, Osaka, Koyama, Okusa, & Kakigi, 1999).

Comparing alpha and beta activity, Papanicolaou, Loring, Deutsch and Eisenberg (1986) and Butler and Glass (1987) showed an inverse relationship (Schier, 2000). Ray and Cole (1985) suggested that alpha activity reflects external events (e.g. sensory information), whereas beta activity reflects internal events (e.g. mental manipulation task). Furthermore, beta activity is mostly studied in the relation with sensorimotor behavior (Gola et al., 2013, for review). Emphasized in the 12-30 Hz band, previous studies have reported a relation between beta rhythm and the preparation or execution of voluntary movements (Alegre, Labarga, Gurtubay, Iriarte, Malanda, & Artieda, 2002; Jasper & Penfield, 1949; Neuper & Pfurtscheller, 2001; Pfurtscheller & Berghold, 1989; Pfurtscheller & Da Silva, 1999; Pfurtscheller, Neuper, Pichler-Zalaudek, Edlinger, & da Silva, 2000; Stančák, Feige, Lücking, & Kristeva-Feige, 2000). Here, Kühn et al. (2004), Androulidakis, Doyle, Yarrow, Litvak, Gilbertson and Brown (2007), and Zhang, Chen, Bressler and Ding (2008) discussed an influence on beta activity in voluntary suppressing movements. The localization of beta activity is mainly found across the primary motor cortex (Müller, Neuper, Rupp, Keinrath, Gerner, & Pfurtscheller, 2003; Salenius, Schnitzler, Salmelin, Jousmäki, & Hari, 1997; Salmelin, Hámáaláinen, Kajola, & Hari, 1995; Salmelin & Hari, 1994). Furthermore, Townsend and Johnson (1979) and Belyavin and Wright (1987) reported a correlation between accuracy levels in a visual vigilance task and beta rhythm in occipito-parietal brain areas. These results are confirmed by further human (e.g. Kamiński, Brzezicka, Gola, & Wróbel, 2012) and non-human studies (e.g. Buschman & Miller, 2007). Age-related differences in beta rhythm were investigated by Gola, Kamiński, Brzezicka and Wróbel (2012). In their study, the authors found that among older adults, beta rhythm over occipital regions correlated with decreased performance.

The gamma rhythm - which has been frequently investigated during recent years - is emphasized over 35 Hz. Considering the gamma rhythm, non-human studies have demonstrated correlations with visual stimuli (Eckhorn, Frien, Bauer, Woelbern, & Kehr, 1993; Singer, 1993), attention (Singer, 1993) and cognitive functions (Fries, Roelfsema, Engel, König, & Singer, 1997; Murthy & Fetz, 1996; Roelfsema, König, Engel, Sireteanu, & Singer, 1994; Roelfsema, Engel, König, & Singer, 1997; Stopfer, Bhagavan, Smith, & Laurent, 1997). Furthermore, in their review Engel and Singer (2001) summarized a relationship between gamma rhythm and visual, auditory, somatosensory, olfactory, motor and memory modalities in a wide range of animal species. Along with animal models, gamma rhythm has also become a topic of intense interest in humans. Here, findings have demonstrated a relation between gamma rhythm and word processing (Eulitz, Maess, Pantev, Friederici, Feige, & Elbert, 1996; Lutzenberger, Pulvermüller, & Birbaumer, 1994; Pulvermüller, Lutzenberger, Preil, & Birbaumer, 1995), classical conditioning paradigm (Miltner, Braun, Arnold, Witte, & Taub, 1999), memory tasks (Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1997, Tallon-Baudry, Bertrand, Peronnet, & Pernier, 1998; Tallon-Baudry & Bertrand, 1999), working memory (Tallon-Baudry et al., 1998), sensory-motor processing (Aoki, Fetz, Shupe, Lettich, & Ojemann, 1999), auditory discrimination (Joliot, Ribary, & Llinas, 1994), somatosensory discrimination (Sauve et al., 1998), the formation of percepts and memory (Pantev, 1995; Singer, 1990; Singer & Gray, 1995), linguistic processing (Pulvermüller et al., 1995), learning (Miltner et al., 1999) and other behavioral and perceptual functions (Llinas & Ribary, 1993; Tiitinen, Sinkkonen, Reinikainen, Alho, Lavikainen, & Näätänen, 1993). For example, Haenschel, Baldeweg, Croft, Whittington and Gruzelier (2000) reported a correlation between gamma rhythm and response to novel auditory stimuli, which is in accordance with previous findings of gamma rhythm in the auditory cortex

(Jokeit & Makeig, 1994; Tallon-Baudry & Bertrand, 1999). In order to test short-term memory, Burgess and Ali (2002) used the Sternberg task with random figures and number words. The authors found increased power in both theta and gamma rhythm. Furthermore, a widespread gamma activity was demonstrated during mental activity by Fitzgibbon, Pope, Mackenzie, Clark and Willoughby (2004). In order to investigate hemispherical differences, Müller, Keil, Gruber and Elbert (1999) showed enhanced gamma power at the right frontal electrodes, regardless of the particular valence. In addition, the importance of the gamma rhythm in considering motor processes has been highlighted by numerous previous studies (Cheyne, Bells, Ferrari, Gaetz, & Bostan, 2008; Crone, Miglioretti, Gordon, & Lesser, 1998; Darvas, Scherer, Ojemann, Rao, Miller, & Sorensen, 2010; Donner, Siegel, Fries, & Engel, 2009; Joundi, Jenkinson, Brittain, Aziz, & Brown, 2012; Miller et al., 2007; Muthukumaraswamy, 2010; Petersen, Willerslev-Olsen, Conway, & Nielsen, 2012; Pfurtscheller, Graimann, Huiggins, Levine, & Schuh, 2003; Seeber, Scherer, Wagner, Solis-Escalante, & Müller-Putz, 2014; Wagner, Solis-Escalante, Grieshofer, Neuper, Müller-Putz, & Scherer, 2012; Wagner, Solis-Escalante, Scherer, Neuper, & Müller-Putz, 2014). While the different rhythms focus on a period of time, event-related potentials represent the direct result of a specific sensory, cognitive or motor event. Richard Caton (1842–1926) who first described event-related potentials observed that ‘feeble currents of varying direction pass through the multiplier when the electrodes are placed on two points of the external surface’. Furthermore, event-related potentials reflect the summed activity of postsynaptic potentials produced when a large number of similarly-oriented cortical pyramidal neurons (in the order of thousands or millions) fire in synchrony while processing information (Peterson, Schroeder, & Arezzo, 1995). Event-related potentials comprise numerous positive and negative voltage deflections and therefore described by a letter (N/P) indicating polarity (negative/positive), followed by a number indicating either the latency in milliseconds or the component's ordinal position in the waveform. The most common event-related potentials can be summarized as follows (see also Sur & Sinha, 2009):

Event-related potentials:	Elicited by:
P50:	sensory gating
N1/N100:	unexpected stimulus
P2/P200:	sensation-seeking
N2/N200:	
N2a/Mismatch negativity:	automatic process during odd stimulus
N2b:	changes in physical property of the stimulus
N2c:	classification of disparate stimuli

P3/P300: stimulus information
N3/N300: semantic congruity and expectancy
N4: semantic incongruity
N6: language processing

Based on the aim of the first experiment, I will especially focus on the P3/300 and the P2/200 components during the following paragraph.

The P3/300 - which occurs at approximately 300ms (250-800ms) or as the third positive peak after a stimulus (Pritchard, 1981; Ritter, Vaughan, & Costa, 1968; Smith, Donchin, Cohen, & Starr, 1970; Sutton, Braren, Zubin, & John, 1965, Sutton, Tueting, Zubin, & John, 1967) - is currently the most-investigated event-related potential. For example, early studies reported a P3/300 in the application of two kinds of stimuli, which differed in the sensory modality (e.g. Sutton et al., 1965). In this context, the peak amplitude of the P3/300 was mostly located over the parietal region (e.g. Picton, 1992; Pritchard, 1981; Vaughan & Ritter, 1970). By contrast, Johnson (1993) and Paller (1994) suggested a multiple generator over different areas, rather than a unitary potential. Based on its characterization, the P3/300 could be further described by its subcomponent P3a / ‘novelty P3’ and P3b / ‘target P3’ (Kok, 2001). The novelty P3 describes a component that occurs during new, non-target stimuli (mostly associated in the context of unintended changes of attention) (Friedman & Simpson, 1994; Spencer, Dien, & Donchin, 1999). Characterized by a longer latency and a more posterior-parietal localization, the P3b is associated with stimulus evaluation in tasks that require some form of action, like a covert or overt response (Donchin, Kramer, & Wickens, 1986a; Kok, 2001).

Considering the general P3/300, both the latency and the amplitude play a highly relevant role. The *latency* is associated with the period of perception (Donchin, 1981) and the difficulty of categorization of a stimulus (Coles, Smid, Scheffers, & Otten, 1995; Courchesne, Hillyard, & Courchesne, 1977; Kutas, McCarthy, & Donchin, 1977). Furthermore, Hoffman, Houck, MacMillan, Simons and Oatman (1985) suggested a relation between latency and the time needed to encode or memorize a stimulus. This includes the clarity of stimuli (Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981) and the number of items stored in short-term memory (Adam & Collins, 1978; Brookhuis et al., 1981; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Gomer, Spicuzza, & O’Donnell, 1976). By contrast, variables on the level of response - such as the compatibility of stimulus-response or the period of motor response - have little or no influence on P3/300 latency (Donchin, 1981; Hoffman et al., 1985). Therefore, the P3/300 is able to classify stimuli independent of the process of response (Donchin & Coles, 1988; Duncan-Johnson & Donchin, 1982). Additional evidence comes from Ila and Polich (1999) using a stroop task. Their results indicated differences in response time but not in the P3/300 latency. Based on these findings, the authors suggested that the behavioral differences are based on the process of response. While the latency is described as reflecting the timing of mental processes, the *amplitude* is mostly related to the intensity of the performance (Donchin et al., 1986a; Donchin, Karis, Bashore, Coles, & Gratton, 1986b; Kok, 1990; Polich & Kok, 1995). In this context, it is assumed that the amplitude represents the demand on the central perceptual resource, respectively the amount of resources dedicated for a task (Kramer & Spinks, 1991; Kramer & Strayer, 1988; Wickens, Kramer, Vanasse, & Donchin, 1983). Nash and Fernandez (1996) investigated the relation between attention-related resources and somatosensory event-related potentials (N140 and P300). In accordance with previous findings (Donchin et al., 1986b; Isreal, Wickens, Chesney, & Donchin, 1980a; Kramer, Wickens, & Donchin, 1985; Sirevaag, Kramer, Coles, & Donchin, 1989; Wickens et al., 1983; Strayer & Kramer, 1990), the authors reported that the P3/300 can serve as an index of the distribution of attention in competing concurrent tasks. Furthermore, Nash and Fernandez (1996) confirmed the assumptions of differences between event-related potentials and behavioral data (Brookhuis et al., 1981; Ford et al., 1979; Ford, Mohs, Pfefferbaum, & Kopell, 1982; Gomer et al., 1976; Kramer & Strayer, 1988; Mecklinger, Kramer, Strayer, 1992; Pelosi, Hayward, & Blumhardt, 1995; Rösler et al., 1986; Verleger, 1997). Previous findings have suggested that the amount of information transmitted during the application of a stimulus is also represented in the P3/300 amplitude (Johnson, 1986; Johnson, 1988; Kok, 1986; Kok, 1997; Parasuraman & Beatty, 1980; Ruchkin & Sutton, 1978; Scheffers & Johnson, 1994; Sutton et al., 1965; Sutton et al., 1967). Within this context, the aspect of attention - which is closely linked to automated and controlled processes (already discussed in the previous chapters) - need to be additionally considered. For example, Hillyard, Hink, Schwent and Picton (1973) concluded that only stimuli that pass through a selection process (and thus require attention) are reflected within the P3/300. This phenomenon was also shown when participants had to switch their attention to another fast-presented stimulus in the same task (Hillyard, 1981; Hillyard & Kutas, 1983; Hillyard, Picton, & Regan, 1978) or when people’s attention drifted away (Johnson, 1988). By contrast, Duncan-Johnson and Donchin (1977) and Squires, Squires and Hillyard (1975) found no differences in the amplitude of P3/300 when participants were instructed to ignore stimuli actively. Investigating the assumption that only controlled tasks require attention, Hoffman et al. (1985) also demonstrated differences in P3/300 amplitude in automated processes of recognition. Therefore, the authors concluded that highly automated processes also require resources of attention. Additionally, Mangun and Hillyard (1990) showed that the higher level of processing used in visual attention tasks is reflected in the amplitude of the P3/300. In their experiment, subjects had to pay attention exclusively to either the left or the right field stimuli or divide attention in different proportions between the two fields.

Studying the P3/300, the so-called oddball paradigm has become one of the most frequently-used paradigms during recent years. First described by Ritter and Vaughan (1969), it comprises the presentation of sequences of repetitive audio/visual stimuli, which are infrequently interrupted by a deviant stimulus. Here, participants are instructed to react / respond to the deviant stimuli. Early findings in non-human studies - for example, by Glover, Onofrj, Ghilardi and Bodis-Wollner (1986) - reported a P3/300 in cynomolgus monkeys. By investigating epileptic patients with electrodes chronically implanted in the medial temporal lobe and other intracranial locations as well as monkeys with epidural, transcortical, and medial temporal lobe electrodes, Paller, McCarthy, Roessler, Allison and Wood (1992) reported a similar pattern of event-related potentials between humans and non-humans using an auditory and visual oddball paradigm. Debener, Makeig, Delorme and Engel (2005) investigated the effects of unique, novel environmental sounds compared to traditional infrequent tones. The authors revealed two independent component clusters that accounted for portions of the novelty P3 and P3b by using the unique, novel environmental sounds. Furthermore, Işoğlu-alkaç, Kedzior, Karamürsel and Ermutlu (2007) combined an auditory-oddball paradigm with passive visual stimulation. Along with a fronto-central location of the P3/300, the authors reported significant larger amplitudes and latencies compared to the ‘classic’ oddball paradigm. Investigating learning effects, numerous studies have reported a decrease in P3/300 amplitude and an increase in latency in repeatedly practicing oddball tasks (Kenemans, Verbaten, Melis, & Slangen, 1992; Lammers & Badia, 1989; Polich, 1989; Wesensten, Badia, & Harsh, 1990).

Along with the oddball paradigm, the P3/300 is frequently discussed in the context of simultaneously performing two tasks. In previous dual-task studies it has been shown that the P3/300 reveals a mechanism of limited capacity and perceived central resources, which are assigned to the task. In an early study, Wickens, Isreal and Donchin (1977) used a visual-tracking task as a primary task and an auditory-oddball task as a secondary task. Task difficulty was increased by increasing the possible dimensions of the visual-tracking task. The amplitude of P3/P300 was measured on the auditory-oddball stimuli. The results showed a decrease in P3/300 amplitude in the dual-task condition compared to the single-oddball task, while there were no differences during the increase of primary task difficulty. Additional evidence comes from Isreal, Chesney, Wickens and Donchin (1980b), who also increased the task difficulty of the primary-tracking task. The authors found an increase in response time in the oddball task with increasing task difficulty but no differences in P3/300 amplitude. Effects of dual- vs. single-taskperformance were identified in both P3/300 amplitude as well as response time. A possible explanation was reported by Donchin (1981), Donchin et al. (1986b) and Kramer and Spinks (1991). Within their experiments, the authors revealed effects in varying perception-related resources but not in manipulating response-related resources. In contrast to others, Wickens et al. (1983) found a decreased P3/300 amplitude with increasing the task difficulty of the primary task. The authors suggested that the tasks compete for a limited capacity and therefore the P3/300 reflects the amount of resources available for the second task. This is in accordance with results reported by Sirevaag et al. (1989). Using relative long inter-stimulus intervals of one second and more, the authors demonstrated a reciprocity of concurrent primary and secondary tasks within different modalities. Combining a visual and an auditory stimulus with a stimulus onset asynchrony of 400ms, Nash and Fernandez (1996) reported a distinct P3/300 for the auditory stimulus, whereas the visual stimulus revealed a reduced P3/300. Polich (1987) demonstrated no interaction between task difficulty and variation of the inter-stimulus interval. Focusing on the role of a limited processing capacity in performing two tasks simultaneously, Hoffman et al. (1985) showed an influence of the distribution of attention on the response time and error rate. Furthermore, the authors reported a reduced amplitude and increased latency in P3/300 under dual- compared to single-task conditions. Investigating the manipulation of stimulus sequence (of the primary-stimuli), Kramer, Wickens and Donchin (1983) demonstrated a decrease in P3/300 amplitude of the secondary stimuli. Cognitive demands and fatigue during the execution of two different motor tasks were analyzed by Schubert, Johannes, Koch, Wieringa, Dengler and Münte (1998). In their study, participants performed an auditory discrimination task as well as different motor tasks (1. required precision and considerable muscle force, 2. required precision but only minimal muscle force). The results showed a reduced P3b amplitude during the force session, indicating that the force task placed a higher demand on cognitive resources. Combining a flight simulator task with an auditory-oddball task, Kramer, Sirevaag and Braune (1987) reported a decrease in P3/300 amplitude in the secondary task, with increasing task difficulty of the simulator task. Similar findings were reported by Strayer and Drews (2007). In their study, participants were asked to perform a driving simulation task while using a mobile phone. In presenting additional stimuli, the P3/300 amplitude decreased in the dual-task driving condition compared to single-task driving (without using a mobile phone). Gramann, Gwin, Bigdely-Shamlo, Ferris and Makeig (2010) used a mobile ‘brain/body imaging’ system, which allows recording high-density electroencephalographic activity and body movements. Here, participants had to perform a visual oddball response task while standing or walking on a treadmill. The results showed no influence of gait on P3/300 amplitude. However, findings of the P3/300 based on dual and oddball paradigms suggested that the amplitude of the P3/300 in a dual-task / oddball setting is influenced by the difficulty of the primary task, albeit only when the primary task is manipulated in the perception-related central domain (Isreal et al., 1980a,b; Kramer et al., 1983; Kramer et al., 1987; Kramer & Strayer, 1988; Sirevaag et al., 1989; Wickens et al., 1977; Wickens et al., 1983).

Another highly relevant event-related potential in the present context, is the P2 or P200, which occurs approximately 150-240 ms after a stimulus. The P2/200 has been discussed in the context of attention (e.g. Maeno, Gjini, Iramina, Eto, & Ueno, 2004), resource allocation (Campbell & Sharma, 2015; Sugimoto & Katayama, 2013), type of stimulus (e.g. Shahin, Roberts, Pantev, Trainor, & Ross, 2005), probability (e.g. Roth, Ford, Lewis, & Kopell, 1976), memory (e.g. Dunn, Dunn, Languis, & Andrews, 1998; Lefebvre, Marchand, Eskes, & Connolly, 2005) and language (e.g. Tonnquist-Uhlen, 1996). Considering the underlying mechanisms of the P2/200, previous studies have revealed several distinct generators comprising at least the anterior auditory cortex, the supra-temporal auditory cortex, the bilateral temporo-parietal cortex and the mesencephalic reticular activating system (Näätänen & Winkler, 1999; Ponton, Eggermont, Kwong, & Don, 2000; Ross & Tremblay, 2009; Tonnquist-Uhlén, 1996; Verkindt, Bertrand, Thevenet, & Pernier, 1994). Similar to the P3/300, attention plays a highly significant role in the amplitude of the P2/200. For example, Maeno et al. (2004), demonstrated changes in parietal and frontal regions at P2/200, related to the amount of attention paid to the stimuli. Motor and sensorimotor processing was also investigated in the context of the P2/200 (but see Huang & Hwang, 2013; Huang, Zhao, & Hwang, 2014; Sibley, Mochizuki, Frank, & McIlroy, 2010). For example, Sibley et al. (2010) showed no differences in the P2/200 as a function of increasing postural demand. In their study, the participants had to react to perturbations while standing at ground level and on an elevated platform (160cm). Participants in the study conducted by Huang and Hwang (2013) had to perform two stance conditions (bipedal and unipedal stance) under static and dynamic force-matching maneuvers. Here, the authors reported differences in the P2/200 between the two conditions, with a smaller P2/200 shown in the right parietal cortex for the dynamic force matching. Another study conducted by Huang et al. (2014) investigated neural control of a postural-supra-postural procedure when postural focus strategy varied. Comparing visual internal and visual external focus, the authors demonstrated an increase in P2/200 around the bilateral fronto-central and ipsilateral temporal areas in the visual external focus condition.

Within the present chapter, the different kind of rhythms of the electroencephalogram have been highlighted. Special attention has been paid to the alpha rhythm, which was discussed in the context of numerous cognitive processes, including memory, attention and perception, intelligence and information processing. The second half of the chapter focused on event-related potentials, especially the P3/300 and the P2/200. Considering the latency of the P3/300, a dependency with the period of perception and the difficulty of categorization of a stimulus was reported, but no or only small effects of stimulus response. In the context of P3/300 amplitude, the representation of the demand on the central perceptual resource - respectively the amount of resources dedicated for a task - were discussed. The results were supplemented by findings of the oddball paradigm as well as dual-task studies. Here, it was summarized that in dual-task / oddball settings, the amplitude of the P3/300 is influenced by the difficulty of the primary task, but only when the primary task is manipulated in the perception-related central domain. Focusing on the event-related potential P2/200, a relationship with attention, resource allocation, type of stimulus, probability, memory and language was stated based on previous findings. Along with the P2/200 localization, dual-task studies reported both no differences in P2/200 as a function of increasing postural demand, but also differences between two postural demands in a dual-task setting.

3. Evidence for the influence of additional demands, task difficulty and the process of aging

The theoretical background highlighted relevant models, existing theories, behavioral and neurophysiological findings as well as individual differences in the field of information processing, executive functions, decision making and dual-task. Across the previous studies, some controversies became apparent. As long as people investigate dual-task situations, there is a constantly reversing debate about humans’ ability to execute two tasks simultaneously. In this context, some researchers suggest a perfect time-sharing, whereas others assume that it is impossible to process two or more tasks at the same time. A similar discussion involves the effects of additional motor demands. In this context, previous findings reported both increased interferences as well as no influences - but also facilitating effects - of simultaneously handling motor demands while executing a cognitive task. Here, the aspect of automatization and thus the amount of attention - paid on the additional motor demand - is frequently discussed. Along with the controversies in healthy middle-aged sample sizes, contrary results are also reported among older adults. In this context, there is an ongoing discussion whether automated processes become more and more controlled during the process of aging. Especially in motor functions, numerous studies suggested an increased necessity of cognitive processes in everyday motor functions - such as walking - with increasing age. By contrast, others argue that a reduced performance of motor functions in dual-task situations based on a decline of attentional capacity or at least physical impairments.

In addition to the controversial findings, some gaps in the research of relevant topics - which became apparent during the theoretical background - need to be highlighted. With a long history, the field of dual-task came up with an uncountable number of studies investigated different aspects from basal stimuli to more complex ones but also applied situations, such as driving. Within these studies, a stystematization of the influence of task difficulty / complexity of combined stimuli is in some way missing. Only a few studies implemented a systematic approach regarding the effects of task difficulty / complexity in dual-task situations. The necessity of considering this aspect in an increasingly systematic way became additionally obvious across the sub-chapter of neurophysiological findings in dual-task. Here, the broad variety of activated structures highlights the aspect that the dual-task paradigm does not comprise two clearly defined tasks. Therefore, it can be accepted that an increasingly systematic investigation of the effects of task difficulty in dual-task situations would lead to a better understanding of humans' ability of executing two or even more tasks simultaneously. Another aspect - which need further consideration - comprises the combination of motor and cognitive tasks, from a neurophysiological perspective. While evidence from functional magnetic resonance imaging is limited to fine motor functions - such as tapping - electroencephalography offers the possibility to get a deeper insight into the cortical mechanisms, which underlies motor functions such as standing. While only a few studies investigated motor / cognitive task combinations, further investigations from an electrophysiological point of view are indispensable.

Based on the previous findings, the upcoming controversies as well as the existing gaps, the following three experiments were developed in order to provide further evidence in this field of research (see also Figure 16):

- Cognitive performance under different demands – Insights from a neurophysiological perspective
- Cognitive performance under different demands – Insights from a behavioral perspective
- Cognitive performance under different demands – Insights from a more applied perspective

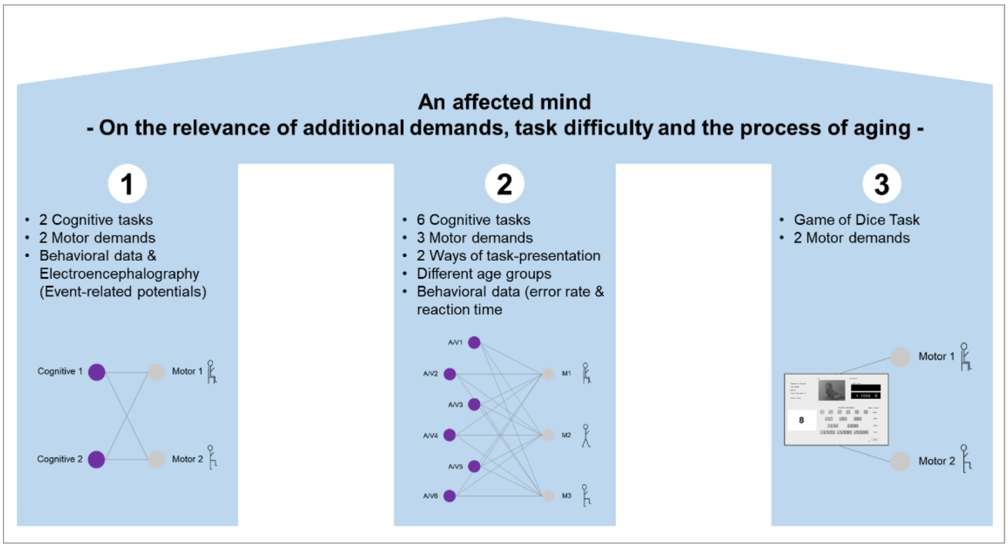


Figure 16 Overview of the three experiments of the thesis at hand.

3.1. Experiment I

Cognitive performance under different demands – Insights from a neurophysiological perspective

‘I did the best thinking of my life on leisurely walks with Amos…’ (Kahneman, 2012; p.40). While Daniel Kahnemann, used this example to demonstrate that not all processes of thinking require intense concentration and effortful computation, numerous previous studies demonstrated occurring interferences in combining motor and cognitive demands (e.g. Klimesch, 1999; Huang, Chang, Tsai, & Hwang, 2016; Liebherr, Schubert, Schiebener, Kersten, & Haas, 2016, for review). Getting a better understanding of the underlying mechanisms, it is inevitable to investigate the simultaneous processing of motion and cognition in a more systematic way. With the current research, I present one of the first investigation of the interplay of simultaneous motor and cognitive demands by using electroencephalography. In particular, the levels of a cognitive task (simple vs. complex decisions) and a concurrent motor demand (sitting vs. one-legged stance) will be examined during an event-related brain potential study. While most event-related brain potential study investigated the simultaneous performance of two cognitive tasks (e.g. Stipacek, Grabner, Neuper, Fink, & Neubauer, 2003), a comprehensive understanding of the effects of cognitive/motor task-combinations is still missing. Since the difficulty/complexity of daily situations is ever growing (e.g. we are standing in the railway while calling a colleague and checking our appointments or we carry out our daily workout while listening to music and writing text messages to our friends), a thorough understanding in particular of the interaction of these tasks will be of utmost importance. Yet how many tasks can humans perform, how much information can they process, and how is this influenced by the type and difficulty of the involved information? While previous research addressed these questions from a behavioral perspective and asked for the amount of information that humans are able to process (e.g. Halford, Baker, McCredden, & Bain, 2005), the main goal of the present study is as follows: Focusing on the event-related potentials of P2/200 and P3/300, the main goal is to investigate potential task interactions between cognitive decision tasks and motor demands. Here, I am interested in the influence of different postural control demands in a motor/cognitive dual-task situation as well as in the effects of varying cognitive task difficulty. I hypothesize first that there is a general interaction between motor demands and cognitive tasks and second that additional motor demands lead to a reduced amplitude of both P2/200 and P3/300 in the primary cognitive task. Furthermore, I assume that increasing task difficulty of the primary cognitive tasks also leads to a reduced P2/200 and P3/300 amplitude. In addition, I expect an increase in error rate with increasing difficulty of the motor and cognitive task.

3.1.1. Material and methods

Participants

In total, 20 right-handed participants, all native speakers of German (mean age 24.1 years, ranging from 20 to 33 years, 15 women) entered the analysis. All reported normal or corrected-to-normal eyesight and no history of neurological or psychological disorder. The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. All participants provided written informed consent prior to the experiment and were informed that they could end participation at any time without reprisal.

Stimuli

In order to investigate the effects of cognitive/motor task interactions as well as task-difficulty, the study comprised of two different motor and two cognitive tasks. Within the ‘easy’ cognitive condition (cog1), stimuli consisted of a letter (A-Z) or a number (1-9) in an equal proportion across the experiment and were presented visually in the center of a computer monitor. The participants’ task was to decide whether the presented stimulus represented a letter or a number. The response to both letters and numbers could be either a reaction or an inhibition stimulus, depending on the specific instructions. The differentiation between reaction and inhibition stimulus was chosen in order to increase task-difficulty. While cog1 included one kind of inhibition and one of reaction stimulus (letter vs. number), the 'difficult' task (cog2) contained two of both. Here, participants had to differentiate between even (2,4,6,8) and odd (1,3,5,7,9) numbers as well as vowels and consonants. Each type of stimulus was presented twenty times and could be either a reaction or an inhibition stimulus. Stimuli were counterbalanced so that both cognitive tasks included 40 reaction and 40 inhibition stimuli. Following the results of Lajoie et al. (1993) who showed that normal standing and walking requires more attention than sitting in a chair, I also used sitting (mot1) as the non-demanding motor task but instead of normal standing or walking, I employed standing on one leg (mot2) as the more demanding motor task. Combining the motor and cognitive tasks, the resulting four task-combinations are illustrated in Figure 17. Each task combination was carried out in a separate block.

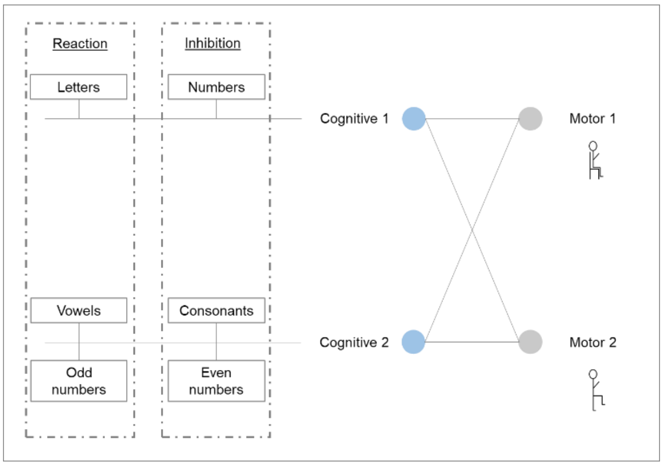


Figure 17 Summarizing the four task combinations.

[(cognitive1/motor1, cognitive1/motor2, cognitive2/motor1, cognitive2/motor2), the left side demonstrates the different cognitive conditions, whereas the used task-combinations are pointed out on the right.]

Procedure

Participants were already prepared and familiar with the measurement system because they previously took part in another, entirely unrelated EEG experiment. Before starting, participants had enough time to rest and give informed consent after carefully reading the instructions. They were informed that they had to attend to both the cognitive and the motor task equally and respond to the cognitive task as fast and as accurately as possible. For the motor condition one leg stance (mot2), they were instructed to freely choose which leg to stand on and change the leg in case of fatigue. Prior to each of the blocks (targeting one of the four task combinations each), participants received a detailed task description. Participants completed the experiment in a shielded cabin with a screen presenting the cognitive tasks. The position of the chair, the screen as well as the standing position were standardized and cross-marked to ensure equal conditions for all participants. For mot2 the screen was heightened to the eye level of the participants. Participants responded with a commercial controller, which was held in two hands, and used the right button in cog1 (one kind of reaction stimuli) and either the left or the right button in cog2 (two kinds of reaction stimuli). Stimuli were presented in the middle of the screen in black against a white background in Deja Vu Sans Mono font (34 pt.), in which all letters and numbers have the same width. Before each individual stimulus, an asterisk was presented for 1000 ms followed by a randomized delay between 1500 ms and 3500 ms. In order to avoid interferences between single cognitive stimuli I chose longer intervals. I randomized the latency between asterisk and critical stimulus to limit predictability of stimulus appearance. Each stimulus was presented for a maximum of 2000 ms or until responding and was followed by a short interval of 100 ms until the next trial was presented. Participants were instructed to blink after a stimulus or while the asterisk was presented. In order to avoid fatigue, participants performed mot2 at the beginning and at the end. To avoid learning effects, simple and difficult cognitive-tasks were used alternately and instructions for responses were changed. Therefore, the two following different sequences of blocks were used and distributed equally across participants: cog1/mot2, cog2/mot1, cog1/mot1, cog2/mot2 or cog2/mot2, cog1/mot1, cog2/mot1, cog1/mot2. The total duration of the experiment was 30 minutes.

EEG recording procedure and preprocessing

In addition to behavioral data (error rate), I recorded the electroencephalogram (EEG) from 26Ag/AgCI scalp electrodes mounted on the scalp by an elastic cap (Electro-Cap Internatiοnal). Electrode position conformed to the international 10-20 system. The EEG was digitized at a rate of 500 Hz and amplified by a Brain Vision Brain-Amp amplifier. Electrode impedances were kept below 4 kΩ. The EEG was referenced online to the left mastoid and re-referenced offline to linked mastoids. I placed the ground at AFz, three electrodes around the subject's right eye (over and under the eye and at its outer cantus) and one electrode at the outer cantus of the left. The eye electrodes served to control for artefacts from eye movement. To avoid slow signal drifts, the EEG data were processed offline with a 0.3–20.0 Hz band pass filter. To exclude trials containing ocular or movement-related artifacts, automatic (±40 μV for the EOG electrodes) and manual rejections were performed. Items with false responses and time-outs as well as ocular and movement artefacts were removed (number of discarded items per condition: cog1/mot1 11.08±10.55, cog1/mot2 9.35±8.84, cog2/mot1 4.63±4.63, cog2/mot2 7.50±7.62).

Data analysis

For behavioral data, error rates were analyzed using repeated-measures analysis of variance (ANOVA) with the factor MOTOR (2 levels: mot1/mot2) and COGNITION (2 levels: cog1/cog2). Furthermore, outliners were identified by using the Tukey test (Tukey, 1977), for each condition:

$$\text{Quantil}0{,}25 - 1.5 * \text{interquartile range} \leq x \leq \text{quantil}0.75 + 1.5 * \text{interquartile range}$$

While x describes the range of values accepted for further evaluation, others were excluded in order to avoid effects based on confusion of triggers, consciously answering wrong or similar. In contrast to the approach of choosing 3-times of the interquartile range, 1.5-times was used to get a more conservative consideration. After excluding the outliners (4 participants), mean values and standard deviations of error rate were calculated for each condition.

ERPs were time-locked to the onset of the stimulus and averaged per participant, condition and electrode for a time window from -200-900 ms. Statistical analyses were calculated for by means of ANOVAs with the factor MOTOR (2 levels: mot1/mot2) and COGNITION (2 levels: cog1/cog2). The EEG-analyses additionally included the factor region of interest (ROI) with five levels, which included the following electrodes: frontal (F3/4, Fz, F7/8), frontocentral (FC1/2, FCz, FC5/6), central (C3/4, Cz, T7/8), centroparietal (CP1/2, CPz, CP5/6) and parietal (P3/4, Pz, P7/8). The critical time-windows were predefined by visual inspection, yielding an early window (200-300 ms) and a later window (350-500 ms).

3.1.2. Results

Considering behavioral results, participants showed relatively low error rates under all conditions. While the simple cognitive task lead to a mean error rate of 0.31±0.52 under sitting condition, error rate increased to 0.47±0.81 in the one-legged stance. In contrast, participants received same mean values of error rate in the difficult cognitive task under sitting and one-legged stance condition (cog2/mot1 0.53±0.84; cog2/mot2 0.53±0.77) (see also

Figure 18). Statistical analysis revealed no significant effects neither for the factor motor nor cognition.

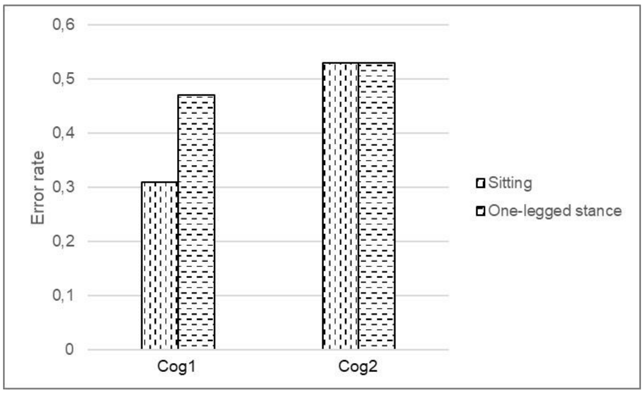


Figure 18 Error rate of the four task-combinations.

Figure 19 illustrates the grand average ERPs for all four conditions at selected electrode sites. It shows an intricate interaction of the two factors in an early time window between 200-300 ms indicating a reversal of the influence of the cognitive task as a function of the motor task; this effect is reflected in a more pronounced positivity for the more demanding cognitive task in the one-legged stance (cog2/mot2) with a central maximum and no difference between the two cognitive tasks during sitting. In addition, Figure 19 highlights clear differences between simple and complex cognitive tasks as well as sitting and one-legged stance reflected by positive deflections peaking around 400 ms after stimulus-onset that have a centroparietal maximum (cog1>cog2; mot1>mot2).

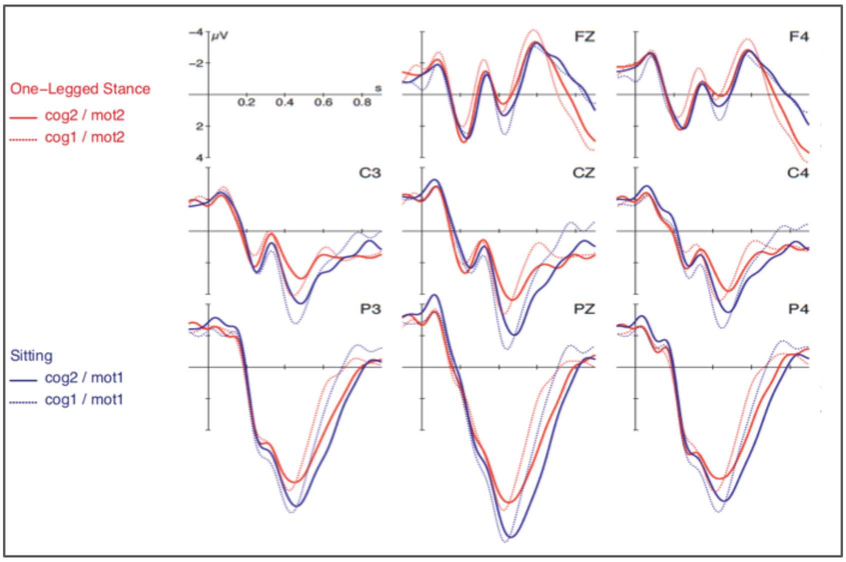


Figure 19 Grand average ERPs for the four combinations of motor task.

[(easy: blue, difficult: red) and cognitive task (easy: dotted, difficult: solid). Negativity is plotted upwards.]

Statistical analysis of the early time window (200-300 ms) registered a motor x cognition interaction [$F(1,19)=5.83$, $p < 0.027$] as well as a cognition x ROI interaction [$F(4,76)=6.07$, $p < 0.013$], which was reflected by more reliable effects over frontal regions. Resolution of the motor x cognition interaction revealed an effect of the cognitive task in the one-legged stance motor condition (mot2) [$F(1,19)=4.32$, $p < 0.051$], which is reflected by a more pronounced positivity for the difficult task (cog2) relative to the simple task (cog1). No significant differences emerged for the simple motor condition (cog1) [$F<0.6$]. Figure 20 illustrates the pair-wise contrast.

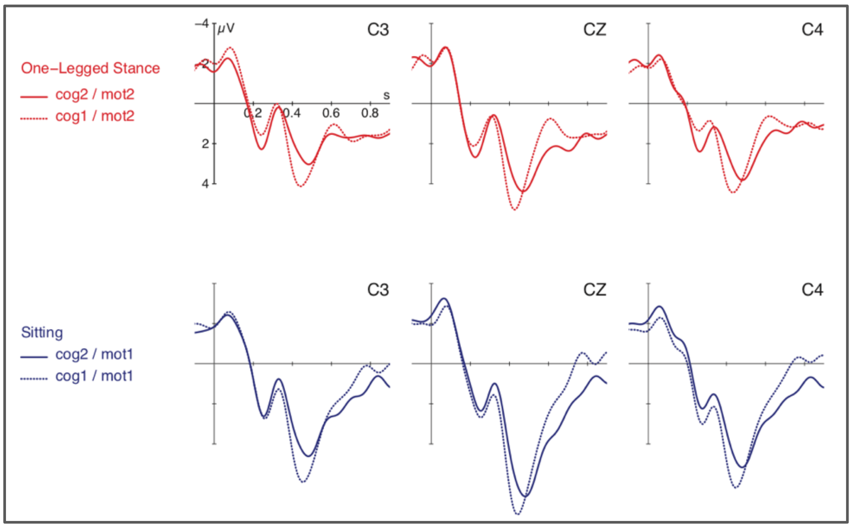


Figure 20 Pair-wise comparisons for the difficult motor task.

[one-legged stance (upper plot) and the easy motor task of sitting (lower plot). Negativity is plotted upwards.]

In the later time window (350-500 ms), the simple cognitive task (cog1) showed a more pronounced positivity than the complex cognitive task (cogn2) (dotted vs. solid lines) and sitting (mot1) evoked a more pronounced positivity than the more complex motor task of standing on one leg (mot2) (blue vs. red lines). Analyzing the time-window between 350 and 500 ms, I found no interaction between motor and cognitive tasks but main effects of the motor task [$F(1,19)=27.09$, $p < 0.001$] and a marginal effect of the cognitive task [$F(1,19)=4.12$, $p < 0.057$]. The interaction with ROI did not reach reliable results.

3.1.3. Discussion

Are cognitive processes facilitated by motor demands and what role does task-difficulty/complexity play in this context? The data first of all suggest that increasing task complexity in both motor demand and cognitive task leads to a reduction of a positivity between

350-500 ms after stimulus onset. Considering the earlier positivity between 200-300 ms, results demonstrate an interaction of cognitive task and motor demand. In the simple motor task (sitting), processing the two types of cognitive tasks did not differ within this time window; by contrast, in the more demanding motor task (one-legged stance), the more difficult cognitive task engendered a more pronounced positivity than the simple cognitive task. This interaction might be due to the amount of attention spent on the tasks. In the following, I first discuss the interaction in the P2/200 window and the effects in the P3/300 window before I address the dissociation of these two processes. In addition, behavioral results, which were not the primary focus of the current study, yielded no reliable effects. Although, I am aware of the fact that the mean error rates are extremely low, and the differences are just tendential, the findings of a decreased range in motor conditions with increasing cognitive task-difficulty, should be addressed in further studies.

As far as the P2/200 interaction between motor and cognitive demands is concerned, I propose that the differences in the amplitude between the easy and difficult cognitive task in the more complex motor task (one-legged stance) (cog2/mot2 > cog1/mot2) are related to an increased resource allocation to the complex cognitive task in one-legged stance in an early stage of processing. Regarding the motor demand, the present findings are in contrast to previous postural control studies, which either reported no effects on P2/200 (Sibley et al., 2010) or a decreased P2/200 with increasing motor demand (Huang & Hwang, 2013). A possible explanation for these differences might be associated with task differences. While the study at hand included a combination of motor and cognitive demand tasks, Sibley and colleagues (2010) for example combined two motor demands without a cognitive component. Furthermore, participants in the study by Huang and Hwang (2013) conducted force-matching manoeuvres (static vs. dynamic) under two stance conditions (bipedal stance vs. unipedal stance).

In contrast to the motor x cognition interaction reported in the P2/200, I found no interaction within a later stage of processing, reflected by the P3/300. This finding is supported by the cross-talk model, which suggests that interferences increase with the degree of similarity of simultaneously performed tasks (see also Pashler, 1994 for review). Accordingly, I suggest a possible parallel processing of motor demand and cognitive task within a later stage of information processing.

Crucially, the current data demonstrate a clear influence of both cognitive and motor task complexity on the P3/300 amplitude, which is in contrast to previous studies (cf. Gramann et al., 2010 for standing vs. walking vs. running). I argue that this difference across studies is due to the type of task used in our study. Based on various previous findings, I propose that the demand on central perceptual resources, respectively the effort spent for the task as well as the amount of information (cf. e.g. Sutton et al., 1965; Wickens et al., 1983) (Kok, 2001 for an overview) are somehow lesser in normal standing, walking and running (as investigated by Gramann et al., 2010; Sibley et al., 2010) compared to the one leg stance used in the current study. Thus, there seem to be particular demands associated with the complex motor task implemented in the present design. Concerning the effect of the motor task (mot1 > mot2), the amount of attention paid to the secondary task is again highly relevant. In addition, the P3/300 is regarded as attention associated with bottom-up information, which is supported by numerous oddball studies (Isreal et al., 1980b; Kida, Kaneda, & Nishihira, 2012; Kramer et al., 1987). Furthermore, Hillyard et al. (1973) concluded that only stimuli that are engaged in a selection process and therefore are paid attention to are reflected by the P3/300. Ignoring a stimulus actively and therefore not allocating any attentional resources to this stimulus leads to the absence of a P3/300 (cf. e.g. Squires et al., 1975). Similar results were obtained when people were asked to concentrate on a quickly presented, relevant stimulus (Hillyard, 1981; Hillyard, & Kutas, 1983) or when their attention drifted away from a performed task (Duncan-Johnson & Donchin, 1977; Johnson, 1988). While gait is generally described as a highly automated task – but see Hoffman et al. (1985) who showed that certain automated detection processes require attentional resources – it could be argued, that standing on one leg needs more attentional resources in a later period of processing which is therefore reflected in a decrease of P3/300 amplitude for the motor task.

The same accounts for the main effect of the cognitive task (cog1 > cog2). While both tasks of the present investigation elicited a P3/300, I suggest that the decrease in amplitude from the easy to the more difficult cognitive task reflects the increasing task difficulty of the cognitive task. Based on previous findings it could be assumed that the increase of task variables from letters and numbers to a finer distinction between even and odd numbers as well as vowels and consonants leads to an increasing amount of cognitive resources necessary for completing the tasks. Similar to the consideration of motor/cognitive task-combinations, previous studies revealed conflicting results in varying task difficulty of the simultaneous performance of two cognitive tasks. On the one hand, Wickens et al. (1977) and Isreal et al. (1980b) among others, who combined a tracking task and an oddball task, showed no differences in P3/300 with increasing task difficulty of the tracking task. On the other hand, Isreal et al. (1980a) reported a decrease of P3/300 amplitude with increasing task difficulty using auditory and visual tasks as well as a combination of both. In this latter study, task difficulty was varied by increasing the number of stimuli (visual task), the type of response (auditory task) as well as in combining the tasks. Furthermore, numerous previous studies reported a delay in P3/300 latency as well as a reduction in P3/300 amplitude with increasing display load (Brookhuis et al., 1981; Hoffman, Simons, & Houck, 1983; Lorist, Snel, Kok, & Mulder, 1996; Smid, Lamain, Hogeboom, Mulder, & Mulder, 1991; Wijers et al., 1987). Additionally, the present findings are supported by Kramer et al. (1987) and Strayer and Drews (2007) who reported a decreased P3/300 amplitude with increasing task difficulty, on a more applied level. While Kramer et al. (1987) combined a flight simulation-task with an additional auditory oddball task, participants within the study conducted by Strayer and Drews (2007) simultaneously performed a driving and mobile phone task.

Finally, for a better understanding of the dissociation of the two temporally distinct effects, attention may be differentiated between willful, top-down processes and bottom-up processes, corresponding to the P2/200 and P3/300 respectively. Previous findings that reported the emergence of a P2/200 in the context of frequent stimuli support the assumption that the P2/200 is associated with top-down processes (Crowley & Colrain, 2004; Federmeier, Mai, & Kutas, 2005; Verleger, Heide, Butt, & Kömpf, 1994). With Maeno et al. (2004) who demonstrated a positive correlation between the P2/200 and the amount of attention allocated to a particular task, the more demanding motor task of the current experiment may facilitate the amount of attention paid to the difficult cognitive task. This indicates that allocation of top-down attentional resources is positively affected by the more complex motor task. In accordance with the cross-talk theory (first described by Paulhan, 1887), which focuses on the content of combined tasks, I suggest that the amount of difficulty/complexity of each task plays a crucial role with respect to the supporting or competing effect of combining two tasks.

Even though I am aware of the limitations of this first study on the subject matter, it demonstrates the possibilities and benefits of systematically investigating the effects of additional tasks/variables. Especially in the light of the rapidly growing complexity of task requirements, further variables such as environmental factors, individual traits, and emotional effects need to be considered next to additional motor tasks and further degrees of task difficulty. Based on the present findings, future studies should focus on a systematic investigation of the factors involved in dual-task processing in order to get a better understanding of task interaction and demands. Overall, I investigated the effects of motor and cognitive task demands in a dual-task setting. I observed an early interaction of the two tasks reflected in a more pronounced P2/200 for the difficult cognitive task in the difficult motor task (one-legged stance), which I associate with increased allocation of top-down attentional resources. This is followed by main effects of complexity for both the motor and the cognitive task, with more reduced P3/300 amplitudes for the more complex tasks, explained inter alia by bottom-up attentional resources.

3.2. Experiment II

Cognitive performance under different demands – Insights from a behavioral perspective

„Any man who can drive safely while kissing a pretty girl is simply not giving the kiss the attention it deserves" (Albert Einstein, 1879-1955).

As discussed in numerous dual-task studies, Albert Einstein - probably unconsciously - described the consequences of performing two tasks simultaneously. Considered since more than 100 years in a multitudinous amount of studies out of numerous fields of interest (e.g. Solomon & Stein, 1896) the questions of how many tasks humans can perform, how much information they can process, and how this is influenced by the type and difficulty of the involved information, which I have already stated in the first experiment, are still not fully answered. While previous research in the context was mostly addressed on a specific question, for example on the influence of using a mobile phone while driving a car, I am of the opinion that it is inevitable to investigate the influence of amount, type and difficulty of simultaneous performed tasks in a more systematic way. Furthermore, individual aspects, which are reported to influence dual-task performance, need to be considered. Based on the first experiment as well as previous findings, the study at hand, focused in a more extensive way the influence of simultaneously performing cognitive and motor tasks as well as task-difficulty, from a behavioral perspective. These aspects will be supplemented by investigating the process of aging but also the way of task-presentation in this context.

Therefore, the present study addresses the following hypotheses, which consider the four different main effects:

1a) Increasing cognitive task difficulty lead to an increased response time.
1b) Increasing cognitive task difficulty lead to an increased error rate.

2a) Increasing difficulty of additional motor demands lead to an increased response time when performing a cognitive task simultaneously.
2b) Increasing difficulty of additional motor demands lead to an increased error rate when performing a cognitive task simultaneously.

3a) Increasing age lead to an increased response time in cognitive task performance under both single- and dual-task conditions.
3b) Increasing age lead to an increased error rate in cognitive task performance under both single- and dual-task conditions.

4a) Different way of cognitive task presentation (visual / auditory) lead to differences in response time under both single- and dual-task conditions.
4b) Different way of cognitive task presentation (visual / auditory) lead to differences in error rate under both single- and dual-task conditions.

In addition to the hypothesis of main effects, the possible interaction effects (combinatorics formula: $2^n - n - 1$, here with $n = 4$), lead to 11 sub-hypothese, which are not further formulated but outlined within Figure 21.

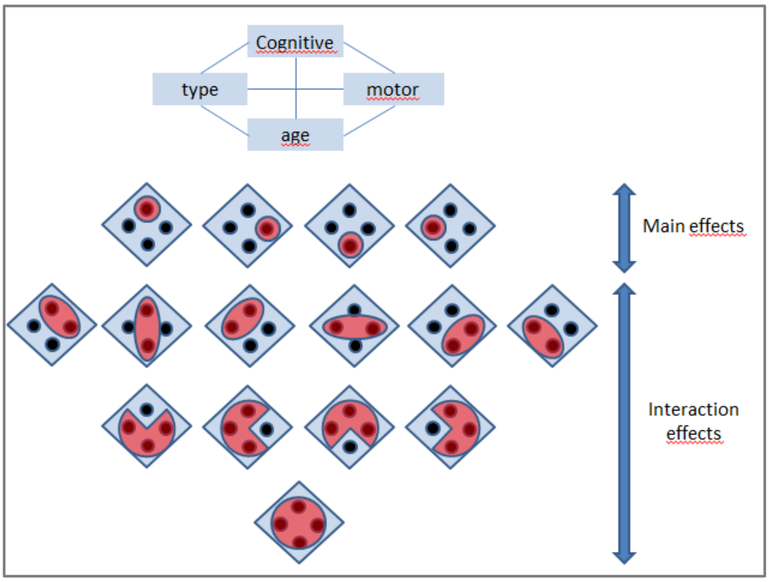


Figure 21 Resulting hypotheses of main- and interaction effects according to set partitioning.

3.2.1. Material and methods

Participants

Fifty people ranging from 20-80 years (mean 45.24 ± 17.17) participated in the present experiment (42 female; 48 right-handed). Participants were recruited from the Hochschule Fresenius (Idstein), regional organisations, as well as public facilities. Aiming a broad age associated variety, I randomized ten of each decade from age 20 to 60 and ten from 60 to

80. People above 60 were tested by the ‘DemTect-Test’ (Kalbe et al., 2004; Kessler, Calabrese, Kalbe, & Berger, 2000) and excluded even when they showed mild limitations or first signs of dementia (DemTect<13). Furthermore, participants reported normal or corrected-to-normal eyesight as well as hearing abilities and no history of acute or chronic diseases (e.g. stroke, joint replacement, Parkinsons disease, etc.), associated with cognitive and / or motor impairments.

Detailed information about the five subgroubs are shown in Table 3. Mean age of each subgroup is additionally visualized in Figure 22.

Table 3 Characteristics of the study sample.

Group	Age	Sex		Hight (cm)	Weight (kg)	Dominant hand		Education		
		m	f			left	right	Level 1	Level 2	Level 3
20-30	22.0±2.7	1	9	166,6±7.6	59.0±7.3	1	9	0	0	10
30-40	32.8±3.3	1	9	169.8±6.0	63.4±8.5	0	10	0	0	10
40-50	46.1±2.7	1	9	172.1±7.8	72.1±11.4	1	9	0	2	8
50-60	55.7±2.5	3	7	174.6±9.7	73.2±12.2	0	10	0	3	7
60-80	69.6±6.6	1	9	166.1±5.7	66.4±7.0	0	10	3	1	6
[level 1: primary school; level 2: secondary modern school; level 3: grammar school]										

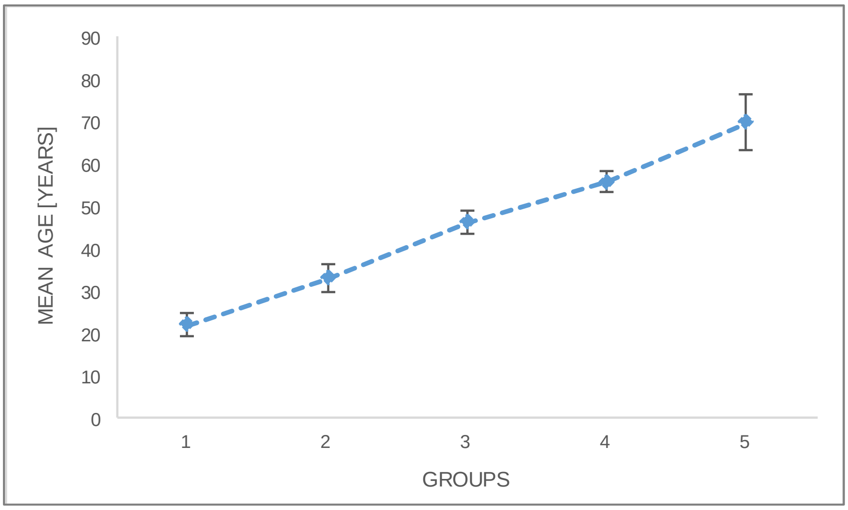


Figure 22 Mean age of each subgroup.

Stimuli

In order to present cognitive tasks under different motor demands on the one hand and to measure response time and error rate on the other hand, a measurement system was developed. The system comprises a personal computer, the measurement software, which is based on the data acquisition program DASYLab®, a bus-powered isolated USB M Series multifunction data acquisition module (National InstrumentsTM), and two homemade triggers, which can be held each in one hand and activated with one finger. For stimulus-presentation, commercial loudspeakers and a flatscreen (21.5”) were used. Cognitive tasks comprise six types of tasks with increasing task-difficulty from a simple reaction-task to a dichotomous choice and double inhibition task with additional mnemonic component. Each task would be presented in both an auditory (A) and a visual (V) way, equal in content. Task-difficulty is regulated by the number of presented stimuli as well as the changing content of the tasks and the possibilities to response during five cognitive tasks.

The systematic characterization of increasing task-difficulty is based on the idea of bipartite graphs out of the mathematical field of graph theory. Therefore, it might be helpful giving a short introduction in the graph theory as well as bipartite graphs, before focusing the content of cognitive tasks in more detail. In the mathematical field a graph is defined as an ordered pair $G = (V,E)$ of a disjunct set with $E \subset V^2$, where the elements of E are 2-element subsets of V. While elements of V are described as vertices of the graph G, elements of E are described as edges (Diestel, 2010). The example of a public transportation map (Figure 23) is a helpful way to describe how vertices and edges interact. Imagine that each vertice represents a station and each edge a connection between two stations, the mathematical understanding of graphs should become obvious.

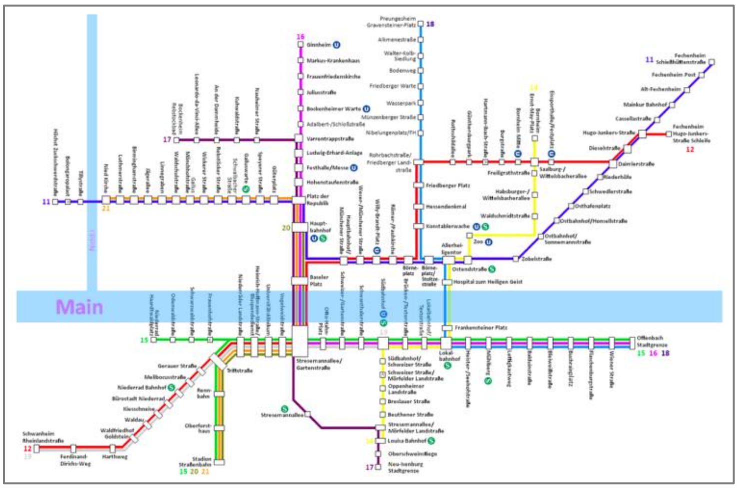


Figure 23 Public transportation map for describing vertices and edges.

Without going into more detail of graph theory, I would like to focus on bipartite graphs hereinafter. Here, a graph is described as r-partite ($r \geq 2$ a natural number) when a partition of V exists in r-parts, so that the vertices of each edge lie in different classes of partition. It is not allowed that vertices of the same class are next to each other. While Figure 24 shows both a 3-partite graph (a) as well as a bipartite graph (b,c), bipartite graphs are characterized by two disjoint sets of vertices that are independent of each other (Diestel, 2010). Considering example b) of Figure 24, every edge connects a vertex in the left set to one in the right. Furthermore, a bipartite graph does not contain any circle with odd-length (Asratian, Denley & Häggkvist, 1998).

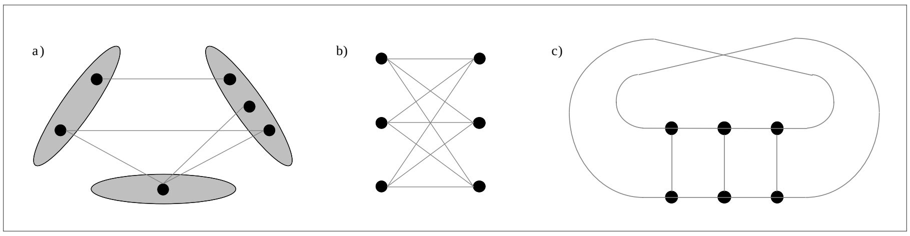


Figure 24 Examples of 3-partite (a) and bipartite (b,c) graphs.

As it is used in describing the increasing task-difficulty of cognitive tasks in the present study (Figure 25), the two different colors of the different sets are based on graph coloring. The idea is, that all vertices of one set have the same color (blue) and the vertices of the other set have another color (green), which leads to the fact that each edge has endpoints of different colors (Scheinerman, 2012). It follows, that each bipartite graph could be colored by exactly two colors.

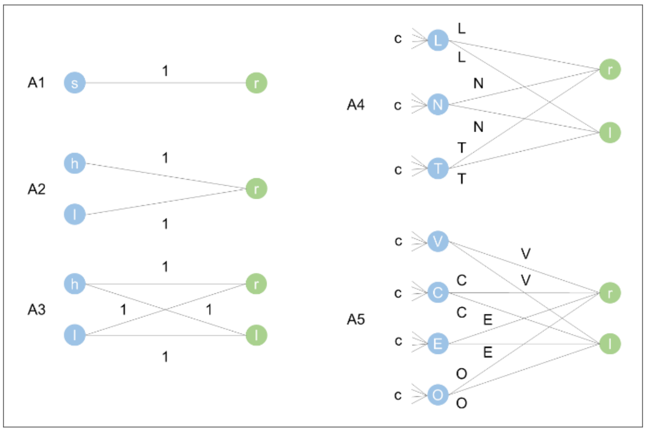


Figure 25 Increasing task-difficulty / complexity on the example of bipartite graphs.

Describing bipartite graphs within the project at hand, Figure 25 drafts five out of the six cognitive tasks with increasing task difficulty from one to five for the auditory task-setting. While the vertices on the left, describe the different kinds of stimuli, presented to the participants, vertices on the right comprising possible responses. Here, the increasing number of edges point out the increase in task-difficulty. Before I go into more detail in describing the content of each cognitive task, some aspects should be stated in the context of Figure 25 before:

- Stimuli used in the present study comprise tones (auditory setting) / points (visual setting), as well as letters and numbers (both settings).
- With increasing task-difficulty stimuli are more separated (e.g. letters and numbers in task 4 and vowels/consonants & even-/odd-numbers in task 5).
- Each of the vertices comprise ten stimuli, taken from a different number of stimuli (out of 26 letters, 9 numbers, 5 vowels, 24 consonants, 4 even-numbers, 5 odd-numbers).
- Responses are related to the used trigger in each task. While in task one and two, participants had only one trigger in their right hand, in task three to five participants have to respond either with their left or right trigger.
- While non-response must be seen as a possible action in each task, task two, four, and five explicitly request participants to inhibit certain stimuli. Here, participants have also the possibility to press a trigger. Therefore, inhibition is not listed as additional vertex within the bipartite graphs.

One might wonder that I have stated six cognitive tasks before, but always talking about cognitive task one to five. This based on the fact that task six could be seen as in somehow specific. This task is equal in content of task five but additionally comprises a mnemonic component, which could not be described by bipartite graphs. In the following, each cognitive task used in the present study will be described in detail (additionally summarized in Table 4).

1. <u>Simple reaction task (A1/V1)</u>
   A single type of stimulus (tone with a frequency of 500Hz / black points, having a diameter of 5cm) would be applied. Participants should answer by using one of the two triggers.
   Amount: 10 response-stimuli.

2. <u>Inhibition reaction task (A2/V2)</u>
   Application of two different type of stimuli (tone with a frequency of either 500Hz or 2000Hz / red or blue points, having a diameter of 5cm). Participants should press one of the two triggers, on one type of stimulus and not react on the other.
   Amount: 10 response-stimuli / 10 inhibition-stimuli.

3. Dichotomous choice task (A3/V3)

   Application of two different type of stimuli (tone with a frequency of either 500Hz or 2000Hz / red or blue points, having a diameter of 5cm), identical to A2/V2. Participants should press one of the two triggers, for the first type of stimulus and the other trigger for the second type of stimulus.

   Amount: 20 response-stimuli.

4. Dichotomous choice and inhibition task (A4/V4)

   Application of different letters (A-Z) and numbers (1-9), equal in the auditory and visual setting. Participants should press one of the two triggers, for letters and the other for numbers. An additional type of stimulus (tone with a frequency of 500Hz / black point, having a diameter of 5cm), would be applied, on which participants should not response.

   Amount: 20 response-stimuli / 10 inhibition-stimuli.

5. Dichotomous choice and double inhibition task (A5/V5)

   Application of different letters (A-Z) and numbers (1-9), equal in the auditory and visual setting. Within this task, I created the subcategories “vowel”, “consonant”, “even number”, and “odd number”. Participants should press one of the two triggers, for one subcategory (e.g. “vowel”), not for the other subcategory out of the same category (e.g. “consonant”). Furthermore, they should press the second trigger for one subcategory of the other category (e.g. “even number”), but not for the other (e.g. “odd number”).

   Amount: 20 response-stimuli / 20 inhibition-stimuli.

6. Mnemonic – dichotomous choice and double inhibition task (A6/V6)

   Equal to A5/V5. Additional, prior to the actual task participants get ten words applied in a visual way for 30 seconds. People should memorize as much as they can of the 10 words across the dichotomous choice and double inhibition task. At the end of the task, people were asked to report as much of the ten words, verbally. The words vary between 2-6 syllables (mean: 3-4 syllables), but the focus in choosing the words was the differences in meaning and its abstract character.

   Amount: 20 response-stimuli / 20 inhibition-stimuli.

Table 4 Summary of the six cognitive tasks.

Cognitive tasks	Task-description	
	visual (v)	auditory (a)
V1 / A1 Simple reaction task	Application of visual signals (black points - response)	Application of auditory signals (tone - response)
V2 / A2 Inhibition reaction task	Application of different visual signals (blue points - response; red points - inhibition)	Application of different auditory signals (high tone - response; low tone - inhibition)
V3 / A3 Dichotomous choice task	Application of different visual signals (blue points - response 1; red points - response 2)	Application of different auditory signals (high tone - response 1; low tone - response 2)
V4 / A4 Dichotomous choice and inhibition task	Application of different letters, numbers and a visual signal (letter - response 1; number - response 2; visual signal - inhibition)	Application of different letters, numbers and a auditory signal (letter - response 1; number - response 2; auditory signal - inhibition)
V5 / A5 Dichotomous choice and double inhibition task	Application of different letters and numbers (vowel - response 1; consonant - inhibition; even number - response 2; odd number - inhibition)	Application of different letters and numbers (vowel - response 1; consonant - inhibition; even number - response 2; odd number - inhibition)
V6 / A6 Mnemonic - dichotomous choice and double inhibition task	Equal to V5 + mnemonic task	Equal to A5 + mnemonic task

The resulting twelve cognitive tasks (6 auditory / 6 visual) were combined with three different motor demands. Following the results of Lajoie et al. (1993) who showed that normal standing and walking requires more attention than sitting in a chair, I also used ‘sitting’ (mot1) as non-demanding motor task, standing as simple motor demand (mot2), but instead of walking, I employed standing on one leg (mot3) as more demanding motor task. In total 36 task-combinations were applied to each participant (Figure 26).

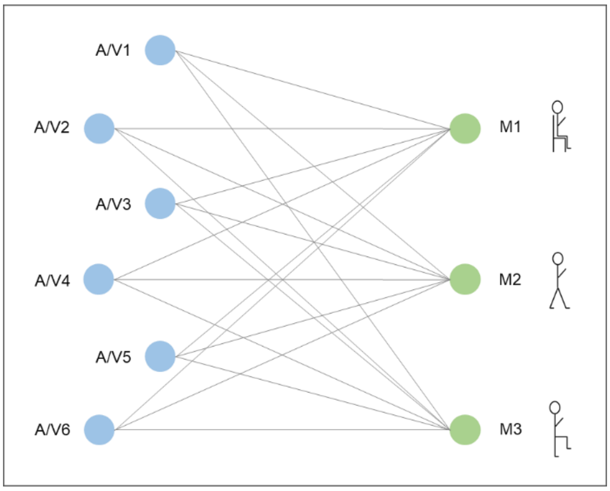


Figure 26 Description of the 18 motor / cognitive task-combinations.

[Both visual and the auditory setting]

Procedure

Before starting, participants give informed consent after carefully reading the instructions. As already stated, people aged above 60 years were tested by the ‘DemTect-Test’ (Kalbe et al., 2004; Kessler et al., 2000) and excluded even when they showed mild limitations or first signs of dementia (DemTect<13). Participants completed the experiment under standardized conditions (e.g. light, noise, temperature, etc.). Furthermore, the position of the chair, the screen as well as the standing position were standardized and cross-marked to ensure equal conditions for all participants. For mot2 and mot3 the screen was heightened to the eye level of the participants. Participants responded with two handmade trigger, held one in each hand, and used the right trigger in cog1 and cog2 and either the left or the right trigger in cog3 – cog6. Stimuli were presented in a randomized way either in the left upper corner, left lower corner, right upper corner, right lower corner, or in the middle of the screen in black against a white background in Deja Vu Sans Mono font (34 pt.), Déjà vu Sans Mono was used due to the fact that all letters and numbers have the same width. Participants were informed that they had to attend to both the cognitive and the motor task equally and respond to the cognitive task as fast and as accurately as possible. For the motor condition one-legged stance (mot3), they were instructed to freely choose which leg to stand on and change the leg in case of fatigue. Prior to each task, participants received a detailed task description.

Before running the study a visual (V1) and an auditory task (A2) were presented to the participants in order to get familiar with the test equipment as well as understand the task description. A2 was chosen to demonstrate participants the difference between a high and low tone. After successfully complete the ‘test-tasks’, the first 18 tasks were applied to the participants. In order to avoide cognitive and motor fatigue, the second 18 tasks were performed on a second time. Here, there was exactly one week off between the first and the second time of measurement. Furthermore, participants were instructed to choose breaks between single tasks whenever they feel fatigue. Within the experiment, all cognitive tasks out of the auditory and visual category are combined in a pseudorandomized way with the three motor demands. In order to avoid motor fatigue two tasks with the motor demand one-legged stance never follow each other. To prevent habituation effects, cognitive tasks of the same level never follow each other (e.g. cog3/mot2 and cog3/mot1). Furthermore, interstimulus interval is randomized between 300-3000ms. Interstimulus interval starts after response of the previous stimulus or 2000ms of its presentation. Therefore, maximum amount of time between two stimuli (in case of non-response or inhibition stimulus) is 5000ms. A delay in stimulus application due to the operating system Windows® and therefore a resulting bias in recording of the response-time is considered in the configuration of the circuit diagram based on the measurement software Dasylab®. Response time and used trigger are saved automatically within the Microsoft program Excel®, by the measurement software. The total duration of the experiment was 2.5 hours.

Data analysis

For the purpose to test for global differences of the mean between different age groups (group factor) and between the different conditions (three repeated-measures factors) the common method is to perform a four-way repeated-measures ANOVA on three within-subjects’ factors. However, a necessity of this analysis is that each participant has been measured on each factor – otherwise from a conservative point of view the whole measurement set of this participant should be excluded from further computations (list wise deletion). In order to cope with missing data, a novel way is to adapt the analysis to perform a mixed-models ANOVA which incorporate both, random and fixed-effects factors (Gueorguieva & Krystal, 2004, Krueger & Tian, 2004). Therefore, the repeated-measure factors (number of levels: motor 3, type 2, cognitive task 6) were treated as simple fixed-effects factors, as the missing data points are assumed to be random samples of the data set. In other words, the conventional wide-data format in which each participant is ordered row-wise with column-wise measurement points was restructured into a long-data format where the repeated-measures factors are arranged row-wise as well. Hence, we got 10*5*3*2*6 = 1080 rows and the columns comprised the 4 factors (age, motor, stimuli, cognitive task) and the two dependent variables (reaction time, number of errors).

As independency between the two dependent variables could not be deduced, henceforth a mixed-models four-way-MANOVA was conducted with three random factors and one fixed factor as stated above. Multivariate significance has been proven with Wilk’s lambda. Global alpha level has been controlled by Benjamini-Hochberg step-up procedure due to hidden multiplicity in this exploratory multiway design (Cramer et al., 2016), that is comparing the p-values (sorted in ascending order) p_1≤p_2≤⋯≤p_m of the m null-hypotheses (main effects and interaction effects) each with α/k with k=1,…,m (Benjamini & Hochberg, 1995). So, the highest p-value p_m was compared with α, p_(m-1) with α/2, etc.
A bivariate analysis on outliers was performed. For this purpose, Mahalanobis distance was calculated and compared with the cut-off value χ^2=13.82 (df=2, p=0.001) (Mahalanobis, 1936). Three more data points were excluded. The dependent variables showed a low correlation of r = 0.354. The assumptions for MANOVA are bivariate normal distribution and homoscedasticity of the residuals both within each factor level. Bivariate normal distribution has been tested by Roystons-H-tests (Royston, 1982, 1983) and a further visual inspection has been done with qq-plots of Mahalanobis-distance for each variable level. Homoscedasticity has been tested first by the Box-M-test and by Levene tests for both dependent variables. Considering MANOVA post-hoc analysis, the Roy Bargman stepdown analysis (Roy & Bargmann, 1958) was used. Here, univariate ANOVA on the dependent variable reaction time has been run. In a second step, a second univariate ANOVA with the dependent variable errors with respect to reaction time as a covariate (ANCOVA) was conducted. This procedure accounts for dependencies between the dependent variables rather than analyzing bivariate significant results on dependent variables independently from each other. Main effects have been analyzed by pairwise conservative Scheffé-tests (due to unbalanced samples). Interaction effects have been analyzed subject to all factor levels using multiple ANOVAs and pairwise independent t-tests. Family-wise alpha level has been controlled using Benjamini-Hochberg step-up procedure when testing familywise tests (multiple ANOVAs or multiple t-tests) or by Scheffé-tests (post-hoc after ANOVA).

3.2.2. Results

Taking into account that each factor is treated as a fixed factor, the conservative procedure to test for multivariate normal distribution is to test on each factor level: only 65 tests of 180 tests showed that the sample was taken from a normally distributed population (p>0.05). Both dependent data sets were consistently right-skewed over each age category (**response time**: (age 20-30 years) S=0.4, (age 30-40 years) S=0.68, (age 40-50 years)

S=0.53, (age 50-60 years) S=0.424, (age 60-80 years) S=0.38; **error rate**: (age 20-30 years) S=1.18, (age 30-40 years) S=1.18, (age 40-50 years) S=1.23, (age 50-60 years) S=1.16, (age 60-80 year) S=1.22) (see Figure 27 & 28). Therefore, this might be an inherent characteristic, which has to be taken into account.

The Box-M-test has been significant (F(489,218708.147)=3.803, $p < 0.001$); furthermore, both Levene-tests showed significant results (RT: F(179,1497)=2.966, $p < 0.001$, error: F(179,1497)=11.0, $p<0.001$). ANCOVA revealed a significant effect of RT on error (F(1,1496)=27.62, $p<0.001$, η^2=0.018). An overview of the result of the MANOVA according to Roy Bargman stepdown analysis is highlighted in Table 5.

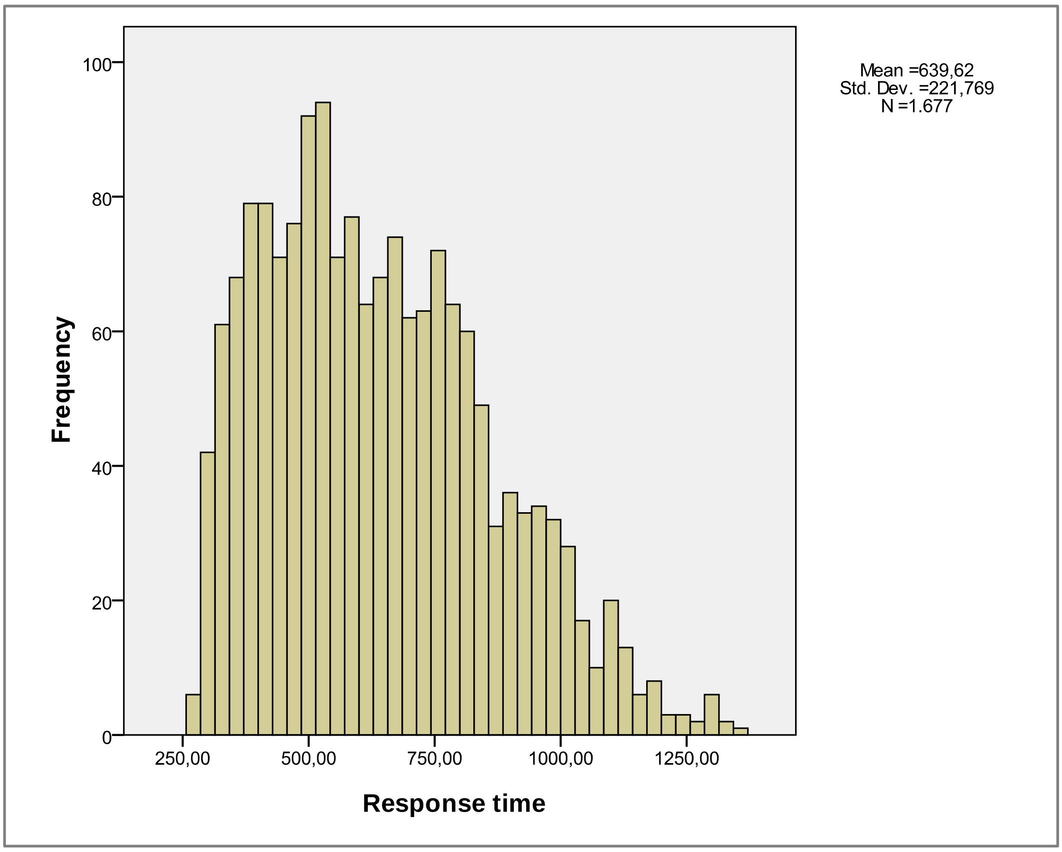


Figure 27 Histogram of the dependent variable response time (absolute frequencies).

[The histogram shows an unimodal distribution but a positive skewness is observable.]

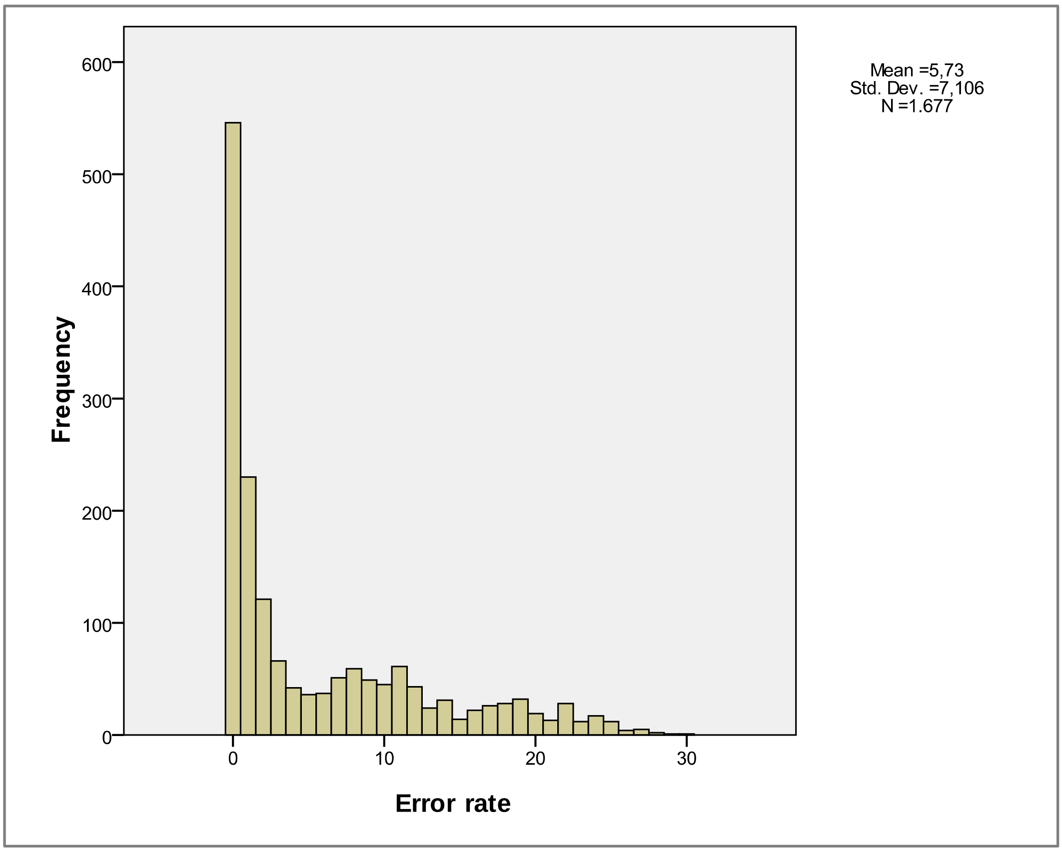


Figure 28 Histogram of the dependent variable error rate (absolute frequencies).

[The morphology of the distribution represents a power law (exponential distribution).]

Table 5 Result of the MANOVA according to Roy Bargman stepdown analysis.

Independent Variables and interactions	MANOVA	ANOVA (RT)	ANCOVA (Error + RT[covariate])	ANOVA / Scheffé test, independent t-tests
Age	F(8,2994)=47.616, p<0.001, η^2=0.113	F(4,1497)=100.368, p<0.001, η^2= 0.211	F(4,1496)=0.784, p=0.536, η^2=0.002	Reaction time: Figure 29
Motor	F(4,2992)=1.843, p=0.118, η^2=0.02	X	X	X
Type	F(2,1496)=224,696, p<0.001, η^2=0.231	F(1,1497)=449.7, p<0.001, η^2=0.231	F(1,1496)=0.002, p=0.965, η^2=0.0	X
Cognitive task	F(10,2992)=407.985, p<0.001, η^2=0.577	F(5,1497)=1108.0, p<0.001, η^2=0.787	F(5,1496)=56.37, p<0.001, η^2=0.16	Reaction time: Figure 30; Error rate: Figure 31

Age*Motor	F(16,2992)=0.619, p=0.871, η^2=0.003	X	X	X
Age*Type	F(8,2992)=1.379, p=0.201, η^2=0.004	X	X	X
Age*Cognitive task	F(40,2992)=2.654, p<0.001, η^2=0.034	F(20,1497)=3.093, p<0.001, η^2=0.04	F(20,1496)=2.22, p=0.001, η^2=0.029	Reaction time: Figure 32; Error rate: Figure 33
Motor*Type	F(4,2992)=8.748, p<0.001, η^2=0.012	F(2,1497)=5.292, p=0.005, η^2=0.007	F(2,1496)=12.22, p<0.001, η^2=0.016	Reaction time: Figure 34; Error rate: Figure 35
Motor*Cognitive task	F(20,2992)=5.137, p<0.001, η^2=0.033	F(10,1497)=5.5, p<0.001, η^2=0.035	F(10,1496)=4.77, p<0.001, η^2=0.031	Reaction time: Figure 36; Error rate: Figure 37
Type*Cognitive task	F(10,2992)=32.0, p<0.001, η^2=0.097	F(5,1497)=63.47, p<0.001, η^2=0.175	F(5,1496)=3.3, p=0.006, η^2=0.01	Reaction time: Figure 38; Error time: Figure 39
Age*Motor*Type	F(16,2992)=1.773, p=0.029, η^2=0.009	X	X	X
Age*Motor* Cognitive task	F(80,2992)=0.901, p=0.722, η^2=0.024	X	X	X
Age*Type* Cognitive task	F(40,2992)=1.164, p=0.223, η^2=0.015	X	X	X
Motor*Type* Cognitive task	F(20,2992)=6.074, p<0.001, η^2=0.039	F(10,1497)=2.25, p=0.013, η^2=0.015	F(10,1496)=9.998, p<0.001, η^2=0.063	Reaction time: Figure 40, Figure 41; Error rate: Figure 42, Figure 43
Age*Motor* Type*Cognitive task	F(80,2992)=0.919, p=0.682, η^2=0.024	X	X	X

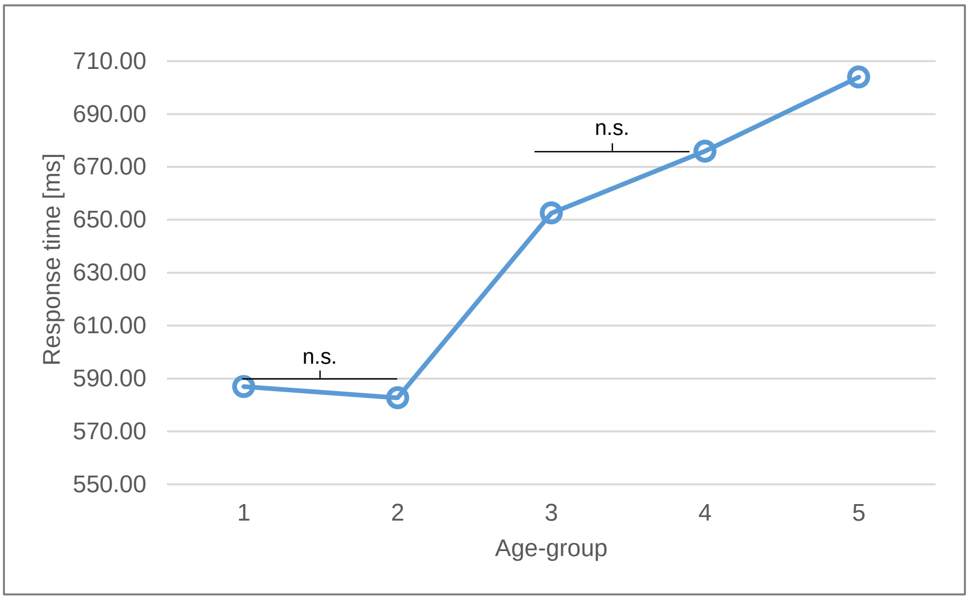


Figure 29 Main effect on age in response time.

Considering the main effect on age, I found significant results with respect to the mean difference (MD) in **response time** on all pairs (3-1: MD=65.58, p<0.001*, 4-1: MD=88.87, p<0.001*, 5-1: MD=116.07, p<0.001*, 3-2: MD=69.8, p<0.001*, 4-2: MD=93.08, p<0.001*, 5-2: MD=120.29, p<0.001*, 5-3: MD=50.49, p<0.001*, 5-4: MD=27.2, p=0.013*), except of the pairs 4-3: MD=23.29, p=0.05 and 2-1 (MD=-4.21, p=0.989).

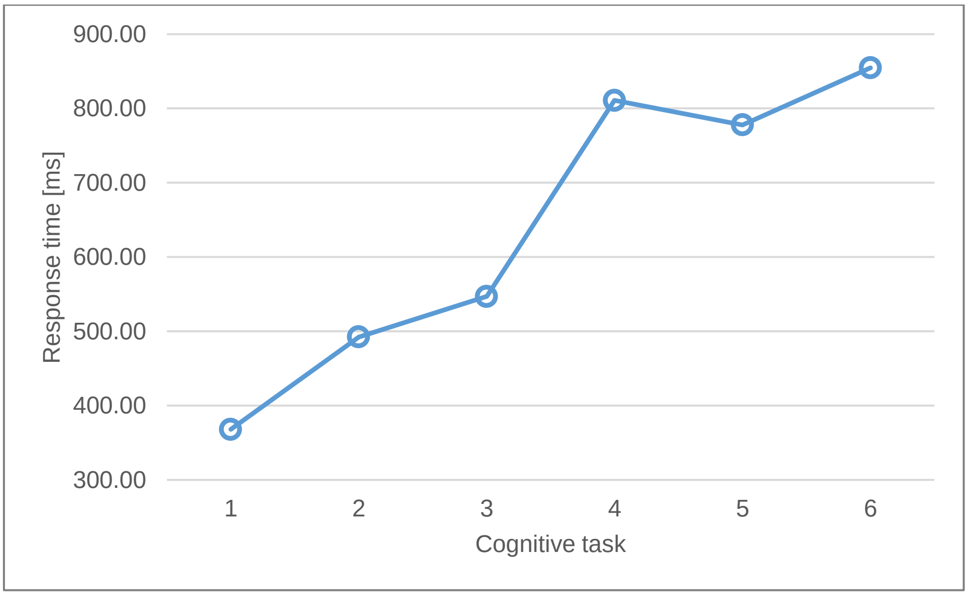


Figure 30 Main effect on cognitive tasks in response time.

With respect to the main effect on cognitive tasks in **response time**, all Scheffé tests showed significant results (2-1: MD=124.29, p<0.001, 3-1: MD=178.8, p<0.001, 4-1:

MD=442.4, p<0.001, 5-1: MD=409.82, p<0.001, 6-1: MD=485.76, p<0.001, 3-2: MD=54.52, p<0.001, 4-2: MD=318.13, p<0.001, 5-2: MD=285.53, p<0.001, 6-2: MD=361.47, p<0.001, 4-3: MD=263.61, p<0.001, 5-3: MD=231.02, p<0.001, 6-3: MD=306.96, p<0.001, 5-4: MD=-32.6, p=0.009, 6-4: MD=43.34, p<0.001, 6-5: MD=75.94, p<0.00).

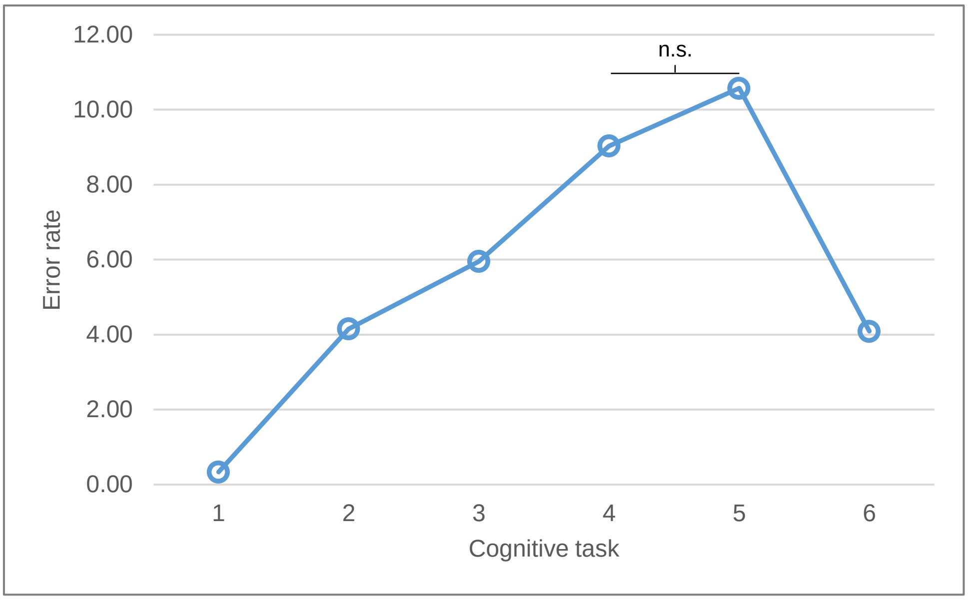


Figure 31 Main effect on cognitive tasks in error rate.

Considering the main effect on cognitive tasks, I found several significances in **error rate**, using Scheffé tests (2-1: MD=3.81, p<0.001, 3-1: MD=5.64, p<0.001, 4-1: MD=8.7, p<0.001, 5-1: MD=10.22, p<0.001, 6-1: MD=3.82, p<0.001, 3-2: MD=1.83, p<0.016, 4-2: MD=4.89, p<0.001, 5-2: MD=6.41, p<0.001, 6-2: MD=0, p=1.0, 4-3: MD=3.07, p<0.001, 5-3: MD=4.58, p<0.001, 6-3: MD=-1.82, p=0.02, 5-4: MD=1.51, p=0.098, 6-4: MD=-4.89, p<0.001, 5-6: MD=-6.4, p<0.001).

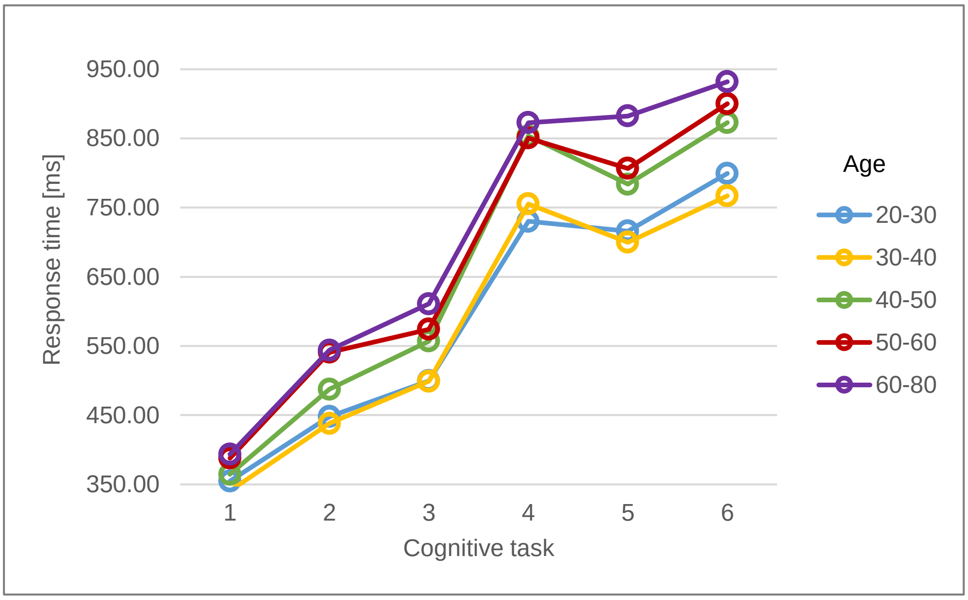


*Figure 32 Effects on age*cognitive task interaction in response time.*

To determine effects in the interaction age*cognitive task in **response time**, I calculated 5 One-way-ANOVAs on cognitive tasks. I found significant effects in all age groups (**age 20-30**: F(5,338)=189.35, p<0.001*, post-hoc Scheffé: 2-1: MD=93.87, p<0.001, 3-1: MD=144.72, p<0.001, 4-1: MD=374.34, p<0.001, 5-1: MD=361.99, p<0.001, 6-1: MD=444.66, p<0.001, 3-2: MD=50.85, p=0.173, 4-2: MD=280.47, p<0.001, 5-2: MD=268.13, p<0.001, 6-2: MD=350.78, p<0.001, 4-3: MD=229.62, p<0.001, 5-3: MD=217.27, p<0.001, 6-3: MD=299.9, p<0.001, 5-4: MD=-12.34, p=0.994, 6-4: MD=70.31, p=0.016, 6-5: MD=82.66, p=0.003; **age 30-40**: F(5,338)=158.99, p<0.001*, post-hoc Scheffé: 2-1: MD=97,59, p<0.001, 3-1: MD=158.37, p<0.001, 4-1: MD=411.93, p<0.001, 5-1: MD=359.15, p<0.001, 6-1: MD=426.12, p<0.001, 3-2: MD=60.78, p=0.089, 4-2: MD=314.34, p<0.001, 5-2: MD=261.56, p<0.001, 6-2: MD=328.53, p<0.001, 4-3: MD=253.57, p<0.001, 5-3: MD=200.78, p<0.001, 6-3: MD=267.75, p<0.001, 5-4: MD=-52.79, p=0.22, 6-4: MD=14.18, p=0.992, 6-5: MD=66.97, p=0.054; **age 40-50**: F(5,338)=178.98, p<0.001*, post-hoc Scheffé: 2-1: MD=123.3, p<0.001, 3-1: MD=192.76, p<0.001, 4-1: MD=489.32, p<0.001, 5-1: MD=420.28, p<0.001, 6-1: MD=509.29, p<0.001, 3-2: MD=69.45, p=0.07, 4-2: MD: 366.02, p<0.001, 5-2: MD=296.97, p<0.001, 6-2: MD=385.98, p<0.001, 4-3: MD=296.57, p<0.001, 5-3: MD=227.52, p<0.001, 6-3: MD=316.53, p<0.001, 5-4: MD=-69.05, p=0.085, 6-4: MD=19.96, p=0.978, 6-5: MD=89.01, p=0.009, **age 50-60**: F(5,342)=137.55, p<0.001*, post-hoc Scheffé: 2-1: MD=153.84, p<0.001, 3-1: MD=186.37, p<0.001, 4-1: MD=462.89, p<0.001, 5-1: MD=419.32, p<0.001, 6-1: MD=509.13, p<0.001, 3-2: MD=32.53, p=0.875, 4-2: MD=309.06, p<0.001, 5-2: MD=265.48, p<0.001, 6-2: MD=355.29, p<0.001, 4-3:

MD=276.52, p<0.001, 5-3: MD=232.95, p<0.001, 6-3: MD=322.75, p<0.001, 5-4: MD=-43.58, p=0.66, 6-4: MD=46.23, p=0.623, 6-5: MD=89.8, p=0.022; **age 60-80**: F(5,319)=128.2, p<0.001*, post-hoc Scheffé: 2-1: MD=151.9, p<0.001, 3-1: MD=216.28, p<0.001, 4-1: MD=479.12, p<0.001, 5-1: MD=493.38, p<0.001, 6-1: MD=538.67, p<0.001, 3-2: MD=64.38, p=0.33, 4-2: MD=327.22, p<0.001, 5-2: MD=341.49, p<0.001, 6-2: MD=386.77, p<0.001, 4-3: MD=262.84, p<0.001, 5-3: MD=277.1, p<0.001, 6-3: MD=322.39, p<0.001, 5-4: MD=14.25, p=0.998, 6-4: MD=59.54, p=0.468, 6-5: MD=45.29, p=0.752). To summarize, when cognitive task-complexity increases response time increases as well. Consecutive significances could be found from cognitive task one to cognitive task two and from cognitive task five to cognitive task six. The greatest increase in response time is observed consistently from cognitive task three to cognitive task four. The increase from cognitive task two to cognitive task three results in marginal response time changes. A general decline (except of the age group of 60-80 years) could be found when regarding cognitive task four and cognitive task five. A comparison with 6 One-way ANOVAs on the age factor revealed significant differences as well (**cognitive task one**: F(4,271)=8.04, p<0.001*, post-hoc Scheffé: 5-1: MD=37.82, p=0.018, 4-2: MD=47.06, p=0.001, 5-2: 52.35, p<0.001; **cognitive task two**: F(4,285)=21.02, p<0.001*, post-hoc Scheffé: 4-1: MD=92.5, p<0.001, 5-1: MD=95.85, p<0.001, 3-2: MD=49.42, p=0.034, 4-2: MD=103.3, p<0.001, 5-2: MD=106.65, p<0.001, 4-3: MD=53.88, p=0.015; **cognitive task three**: F(4,293)=20.72, p<0.001*, post-hoc Scheffé: 3-1: MD=57.22, p=0.005, 4-1: MD=74.18, p<0.001, 5-1: MD=109.38, p<0.001, 3-2: MD=58.1, p=0.004, 4-2: MD=75.06, p<0.001, 5-2: MD=110.26, p<0.001, 5-3: MD=52.16, p=0.018; **cognitive task four**: F(4,281)=7.07, p<0.001*, post-hoc Scheffé: 3-1: MD=124.17, p=0.013, 4-1: MD=121.09, p=0.016, 5-1: MD=142.6, p=0.003, 5-2: MD=119.53, p=0.025; **cognitive task five**: F(4,278)=19.43, p<0.001*, post-hoc Scheffé: 4-1: MD=89.85, p=0.007, 5-1: MD=169.2, p<0.001, 4-2: MD=107.23, p<0.001, 5-2: MD=186.58, p<0.001, 5-3: MD=101.74, p=0.002, 5-4: MD=79.35, p=0.027; **cognitive task six**: F(4,263)=12.4, p<0.001*, post-hoc Scheffé: 4-1: MD=97.0, p=0.016, 5-1: MD=131.84, p<0.001, 3-2: MD=106.88, p=0.005, 4-2: MD=130.06, p<0.001, 5-2: MD=164.9, p<0.001). Consistently, age differences between age group of 20-30 years and 30-40 years versus age group of 50-60 years and 60-80 years exist over all stimulus levels. Age group of 40-50 years is significant different from older age groups when easy tasks are presented, however, when task complexity increases, age of 40-50 years is significant different to younger age groups.

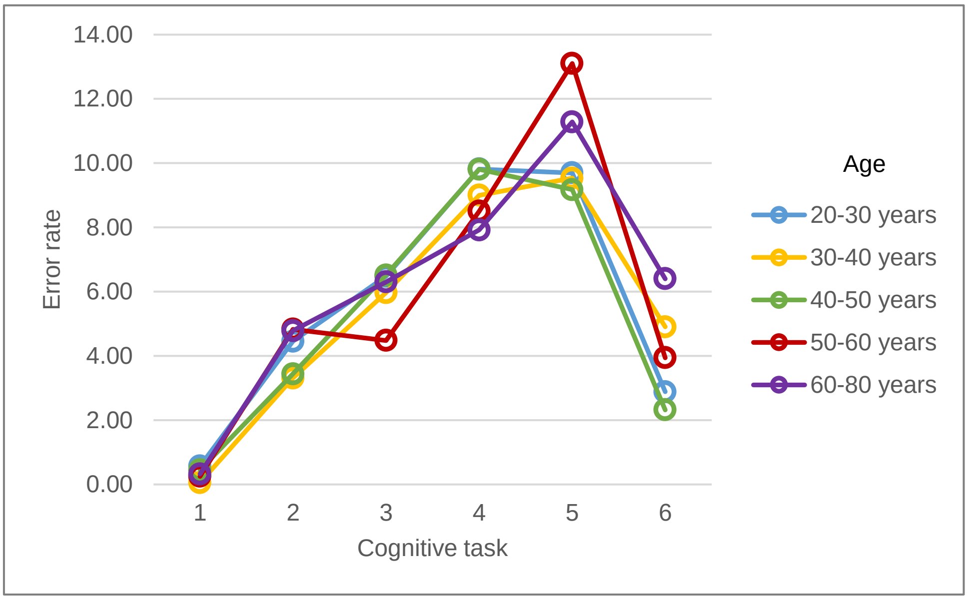


*Figure 33 Effects on age*cognitive task interaction in error rate.*

With respect to the interaction age*cognitive task in **error rate**, five one-way ANOVAs each within the age levels were used to reveal significant differences on the factor cognitive task. I found a significant increase in the numbers of errors with increasing cognitive task complexity until cognitive task four for age groups 20-30 to 40-50; no significances occurred from cognitive task four to cognitive task five and a significant decline in the number of errors occurred from cognitive task five to cognitive task six (**age 20-30**: F(5,335)=19.78, p<0.001*, post-hoc Scheffé: 3-1: MD=6, p<0.001, 4-2: MD=5.22, p=0.002, 5-2: MD=5.24, p=0.002, 6-4: MD=-6.8, p<0.001, **age 30-40**: F(5,338)=17.65, p<0.001*, post-hoc Scheffé: 3-1: MD=5.9, p<0.001, 4-2: MD=5.69, p<0.001, 6-5: MD=-4.63, p=0.012, 6-4: MD=-4.1, p=0.044, **age 40-50**: F(5,338)=23.72, p<0.001*, post-hoc Scheffé: 3-1: MD=6.01, p<0.001, 4-2: MD=6.37, p<0.001, 6-5: MD=-6.85, p<0.001, 6-4: MD=-7.49, p<0.001). In the age groups of 50-60 years and 60-80 years, the same structure as before has been roughly revealed; in addition there has been a significant difference from cognitive task four to cognitive task five, and therefore the decline to cognitive task six is even more decisive (**age 50-60**: F(5,342)=29.06, p<0.001*, post-hoc Scheffé: 2-1: MD=4.6, p=0.009, 5-2: MD=8.3, p<0.001, 5-3: MD=8.62, p<0.001, 5-4: MD=4.6, p=0.007, 6-5: MD=-8.9, p<0.001, **age 60-80**: F(5,319)=15.34, p<0.001*, post-hoc Scheffé: 2-1: MD=4.4, p=0.039, 5-3: MD=4.85, p=0.015, 6-5: MD=-4.75, p=0.023).

Furthermore, the six one-way ANOVAs within the stimuli levels showed some inconsistent differences (**cognitive task one**: F(4,271)=3.59, p=0.007*, post-hoc Scheffé: 2-1: MD=-0.5, p=0.017, **cognitive task two**: F(4,285)=1.448, p=0.218, **cognitive task three**: F(4,293)=1.89, p=0.112, **cognitive task four**: F(4,281)=0.42, p=0.796, **cognitive task five**:

F(4,278)=1.75, p=0.139, **cognitive task six:** F(4,263)=4.412, p=0.002*, post-hoc Scheffé: 5-1: MD=3.52, p=0.039, 5-3: MD=4.1, p=0.009).

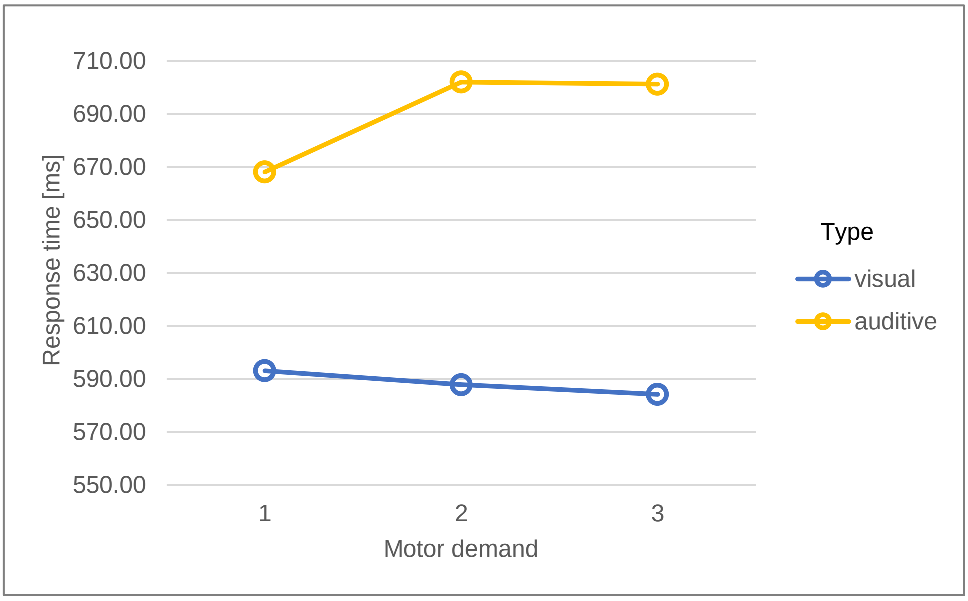


*Figure 34 Effects on motor demand*type interaction in response time.*

With regards to motor demand*type in **response time**, a first analysis with One-way-ANOVAs over the motor demands showed no significant difference (**visual**: F(2,831)=0.172, p=0.842, **auditive**: F(2,844)=1.577, p=0.207). Independent t-tests between the different type of stimuli were significant (sitting (1): t=-4.218, p<0.001*, standing (2): t=-6.02, p<0.001*, one-legged stance (3): t=-6.52, p<0.001*).

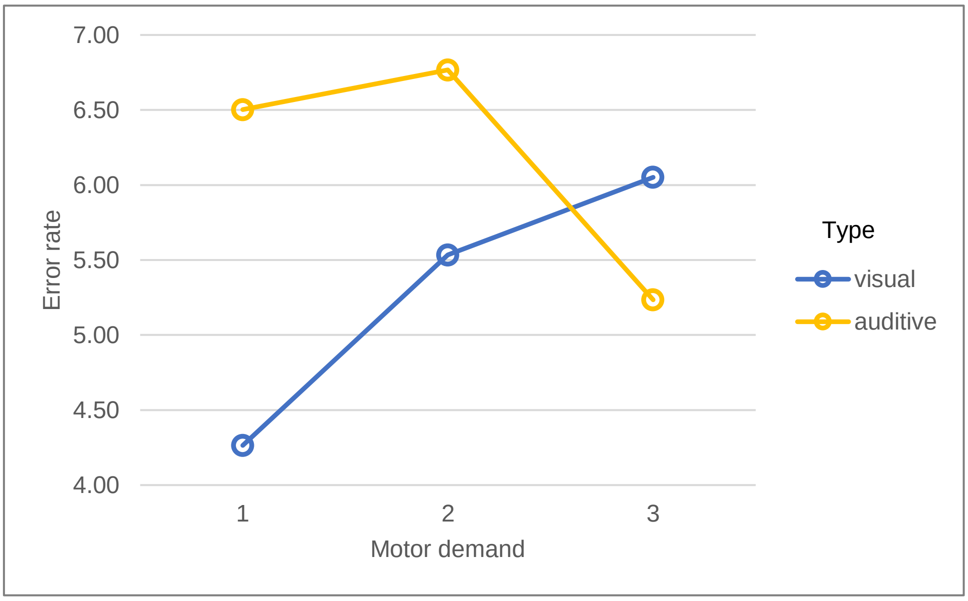


*Figure 35 Effects on motor demand*type interaction in error rate.*

Considering the interaction motor demand*type in **error rate**, two one-way ANOVAs on the factor motor within the factor typ were applied (**visual**: F(2,831)=5.39, p=0.005*, post-hoc Scheffé: 2-1: MD=1.34, p=0.054, 3-2: MD=0.41, p=0.762, 3-1: MD=1.75, p=0.008; **auditive**: F(2,844)=3.32, p=0.037. Independent t-tests were used to describe differences within each motor level (sitting (1): t(559)=-3.967, p<0.001*, standing (2): t(560)=-1.81, p=0.071, one-legged stance (3): t(552)=1.34, p=0.182).

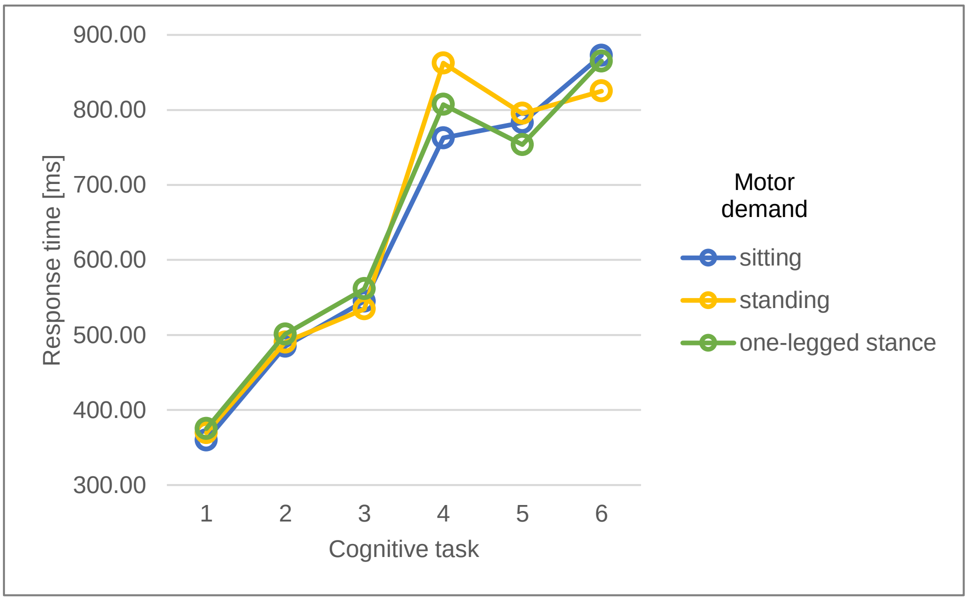


*Figure 36 Effects on motor demand*cognitive task interaction in response time.*

The interaction motor demand*cognitive task in **response time** was first analyzed on cognitive tasks conducting One-way-ANOVAs (**sitting**: F(5,560)=263.73, p<0.001*, post-hoc Scheffé significant except of the pair 5-4; **standing**: F(5,561)=215.9, p<0.001*, post-hoc Scheffé significant except of 3-2, 6-4, 6-5; **one-legged stance**: F(5,553)=199.58, p<0.001*, post-hoc Scheffé significant except of 3-2, 5-4, 6-4). A second analysis was made on motor demands for each cognitive task using One-way ANOVAs (**cognitive task one**: F(2,271)=1.51, p=0.224, **cognitive task two**: F(2,285)=0.763, p=0.467, **cognitive task three**: F(2,293)=2.14, p=0.119, **cognitive task four**: F(2,281)=6.442, p=0.002*, post-hoc Scheffé: 2-1: MD=97.83, p=0.002, **cognitive task five**: F(2,278)=2.18, p=0.115, **cognitive task six**: F(2,263)=2.713, p=0.068).

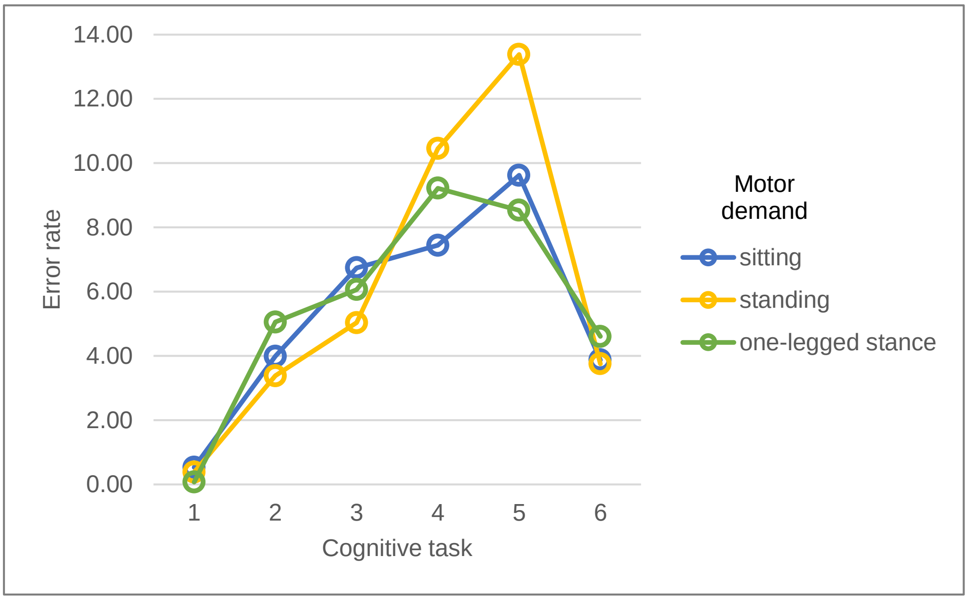


*Figure 37 Effects on motor demand*cognitive task interaction in error rate.*

I found several significant differences when analyzing the interaction motor demand*cognitive task in **error rate**. First, I calculated 3 one-way ANOVAs on the factor cognitive task for each motor level (**sitting**: F(5,560)=25.6, p<0.001*, post-hoc Scheffé: 2-1: MD=3.47, p=0.012, 6-5: MD=-5.66, p<0.001, 6-4: MD=-3.68, p=0.006; **standing**: F(5,561)=57.87, p<0.001*, post-hoc Scheffé: 3-1: MD=4.65, p<0.001, 4-3: MD=5.42, p<0.001, 6-5: MD=-9.44, p<0.001; **one-legged stance**: F(5,553)=23.93, p<0.001*, post-hoc Scheffé: 2-1: MD=4.95, p<0.001, 6-5: MD=-3.93, p=0.003). Second, 6 one-way ANOVAs on the factor motor demand for each cognitive task were conducted (**cognitive task one**: F(2,271)=8.71, p<0.001*, post-hoc Scheffé: 3-1: MD=-0.45, p<0.001; 3-2: MD=-0.31, p=0.02; **cognitive task two**: F(2,285)=3.226, p=0.041; **cognitive task three**: F(2,293)=3.225, p=0.041; **cognitive task four**: F(2,281)=2.91, p=0.056; **cognitive task five**: F(2,278)=7.38, p=0.001*, post-hoc Scheffé: 2-1: MD=3.85, p=0.016, 3-2: MD=-4.85, p=0.002; **cognitive task six**: F(2,263)=0.44, p=0.645).

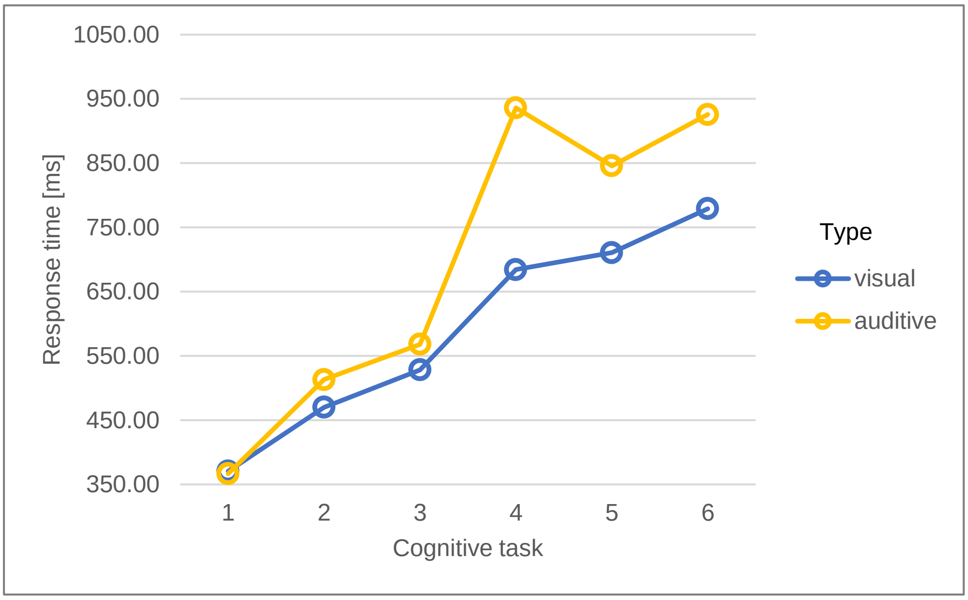


*Figure 38 Effects on type*cognitive task interaction in response time.*

The interaction type*cognitive task in **response time** is processed on the one hand by using One-way-ANOVAs on type (**visual**: F(5,831)=301.77, p<0.001*, post-hoc Scheffé: significant except of 5-4, **auditive**: F(5,844)=598.74, p<0.001*, post-hoc Scheffé: significant except of 6-4). On the other hand, independent t-tests were used to reveal differences on cognitive tasks (**cognitive task one**: t=0.374, p=0.709, **cognitive task two**: t=-4.195, p<0.001*, **cognitive task three**: t=-3.841, p<0.001*, **cognitive task four**: t=-14.07, p<0.001*, **cognitive task five**: t=-8.912, p<0.001*, **cognitive task six**: t=-9.212, p<0.001*). Therefore, cognitive tasks lead to more different response time when stimulus complexity is enhanced.

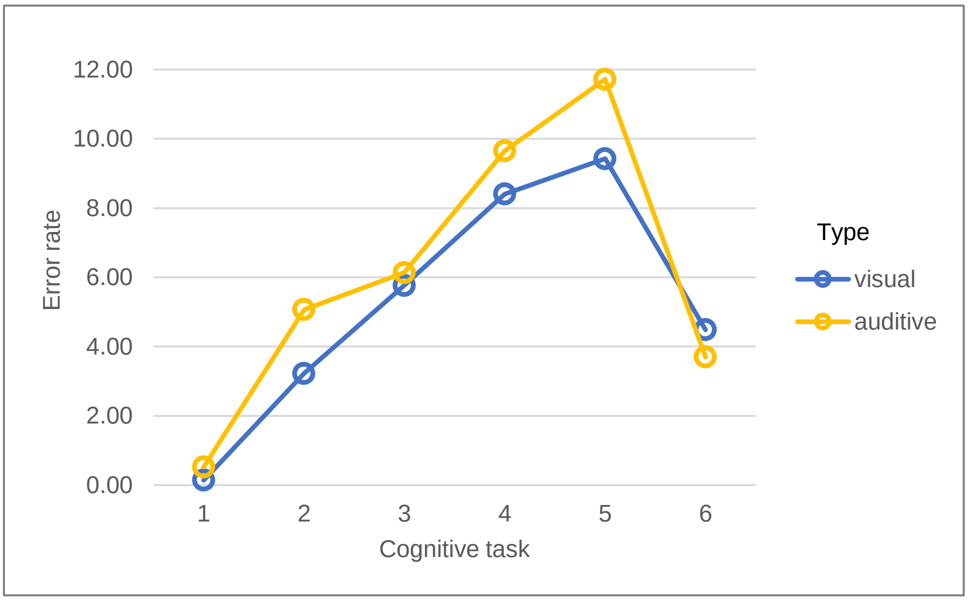


*Figure 39 Effects on type*cognitive task interaction in error rate.*

The interaction type*cognitive task is first analyzed in **error rate** by one-way ANOVAs on cognitive task: I found an increasing tendency of the number of errors with increasing cognitive task-complexity. However, the number of errors declined with the last condition **(visual**: F(5,831)=46.77, p<0.001*, post-hoc Scheffé: 2-1: MD=3.07, p=0.002, 3-2: MD=2.6, p=0.014, 4-3: MD=2.54, p=0.02, 6-5: MD=-4.82, p<0.001, 6-4: MD=--3.73, p<0.001, 6-1: MD=4.47, p<0.001; **auditive**: F(5,844)=52.1, p<0.001*, post-hoc Scheffé: 2-1: MD=4.55, p<0.001, 4-3: MD=3.58, p=0.001, 6-5: MD=-7.98, p<0.001, 6-4: MD=-6.01, p<0.001, 6-1: MD=3.18, p=0.008). Multiple independent t-tests were calculated for each cognitive task (**cognitive task one**: t(270)=-4.34, p<0.001*, **cognitive task two**: t(284)=-3.5, p=0.001*, **cognitive task three**: t(292)=-0.59, p=0.553, **cognitive task four**: t(280)=-1.38, p=0.17, **cognitive task five**: t(277)=-2.01, p=0.045, **cognitive task six**: t(262)=1.28, p=0.201).

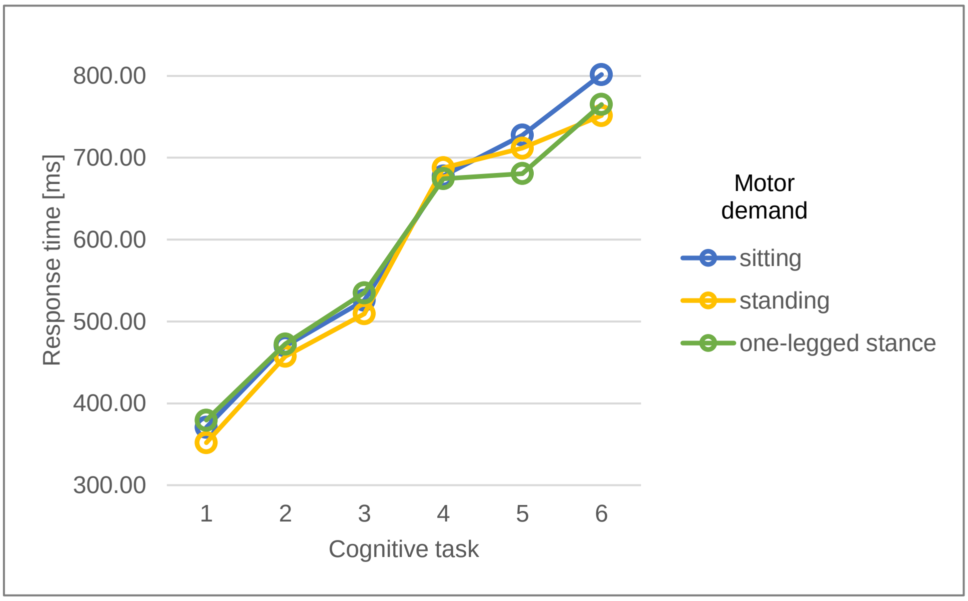


*Figure 40 Effects on motor demand*cognitive task*type [visual] interaction in response time.*

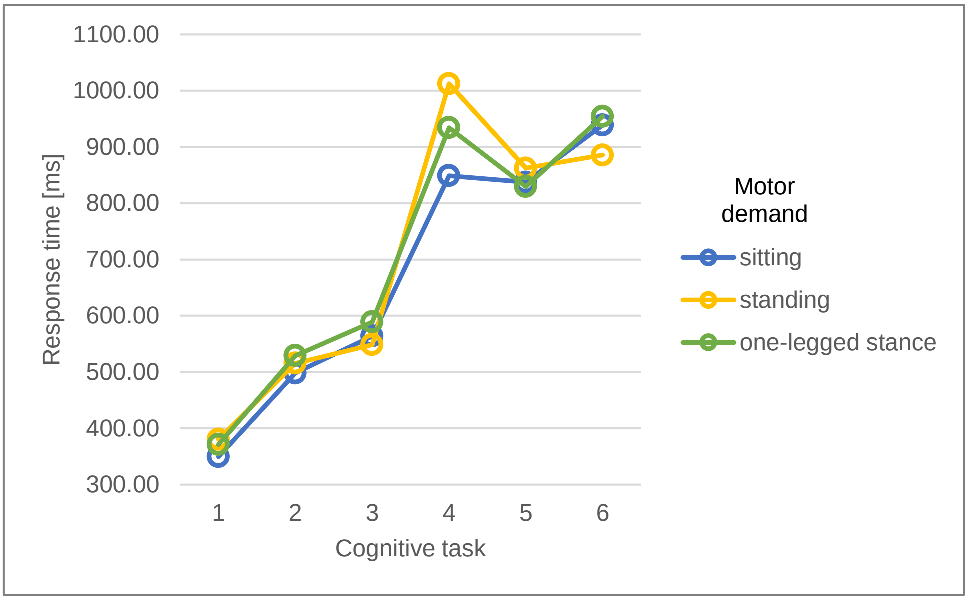


*Figure 41 Effects on motor demand*cognitive task*type [auditive] interaction in response time.*

The interaction effect in motor demand*cognitive task*type has been analyzed in **response time** on the factor cognitive task and on the factor type within each motor demand. In the **visual condition**, I found very similar effects within each motor condition: an increase in cognitive task-complexity lead to increased response time (**sitting**: F(5,275)=110.98, p<0.001*, post-hoc Scheffé: 2-1: MD=99.27, p=0.002, 3-2: MD=55.9, p=0.258, 4-3: MD=151.99, p<0.001, 5-4: MD=49.83, p=0.39, 6-5: MD=74.14, p=0.058, 6-4: MD=123.97, p<0.001; **standing**: F(5,282)=112.13, p<0.001*, post-hoc Scheffé: 2-1: MD=107.43, p<0.001, 3-2: MD=53.23, p=0.302, 4-3: MD=182.66, p<0.001, 5-4: MD=23.84, p=0.946, 6-5: MD=39.02, p=0.681, 6-4: MD=62.85, p=0.163; **one-legged stance**: F(5,272)=81.49, p<0.001*, post-hoc Scheffé: 2-1: MD=92.9, p=0.006, 3-2: MD=62.55, p=0.14, 4-3: MD=139.52, p<0.001, 5-4: MD=6.27, p=1.0, 6-5: MD=84.36, p=0.018). No significances could be found on the factor motor demand within the factor cognitive task (**cognitive task one**: F(2,133)=1.315, p=0.272, **cognitive task two**: F(2,141)=0.043, p=0.958, **cognitive task three**: F(2,146)=0.387, p=0.68, **cognitive task four**: F(2,138)=0.652, p=0.523, **cognitive task five**: F(2,139)=2.28, p=0.106, **cognitive task six**: F(2,129)=1.08, p=0.343). In the **auditive condition** the increase in response time could be found until cognitive task four; thereafter cognitive task-complexity had no consistent effects (**sitting**: F(5,284)=219.59, p<0.001*, post-hoc Scheffé: 2-1: MD=148.68, p<0.001, 3-2: MD=65.72, p=0.117, 4-3: MD=287.37, p<0.001, 5-4: MD=-12.37, p=1.0, 5-3: MD=275, p<0.001, 6-5: MD=99.84, p=0.002, 6-4: MD=87.47, p=0.012; **standing**: F(5,278)=203.64, p<0.001*, post-hoc Scheffé: 2-1: MD=135.25, p<0.001, 3-2: MD=32.98, p=0.878, 4-3: MD=463.81, p<0.001, 5-4: MD=-149.98, p<0.001, 5-3: MD=313.83, p<0.001, 6-5: MD=23.1, p=0.975, 6-4: MD=-126.88, p<0.001, 6-3: MD=336.94, p<0.001; **one-legged stance:** F(5,280)=227.98, p<0.001*, post-hoc Scheffé: 2-1: MD=158.13, p<0.001, 3-2: MD=58.57, p=0.208, 4-3: MD=343.8, p<0.001, 5-4: MD=-102, p=0.002, 5-3: MD=241.77, p<0.001, 6-5: MD=124.89, p<0.001, 6-4: MD=22.85, p=0.958). There has been a significant difference of response time on the factor motor demand within cognitive task four (**cognitive task one**: F(2,137)=3.184, p=0.045, **cognitive task two**: F(2,143)=1.523, p=0.22, **cognitive task three**: F(2,146)=2.213, p=0.113, **cognitive task four**: F(2,142)=13.717, p<0.001*, post-hoc Scheffé: 2-1: MD=160.92, p<0.001, 3-2: MD=80.75, p=0.03; **cognitive task five**: F(2,138)=0.836, p=0.436, **cognitive task six**: F(2,133)=3.25, p=0.042).

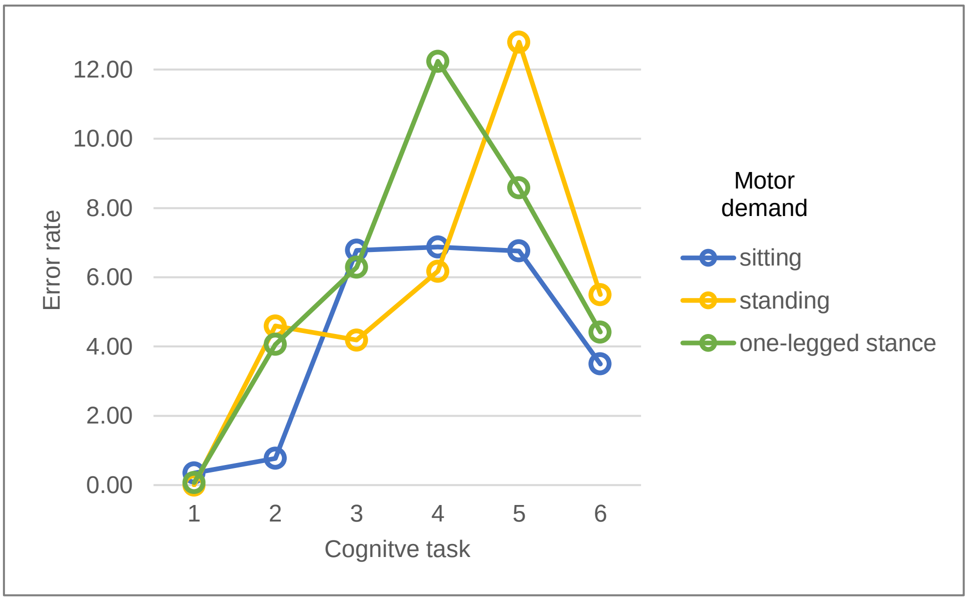


*Figure 42 Effects on motor demand*cognitive task*type [visual] interaction in error rate.*

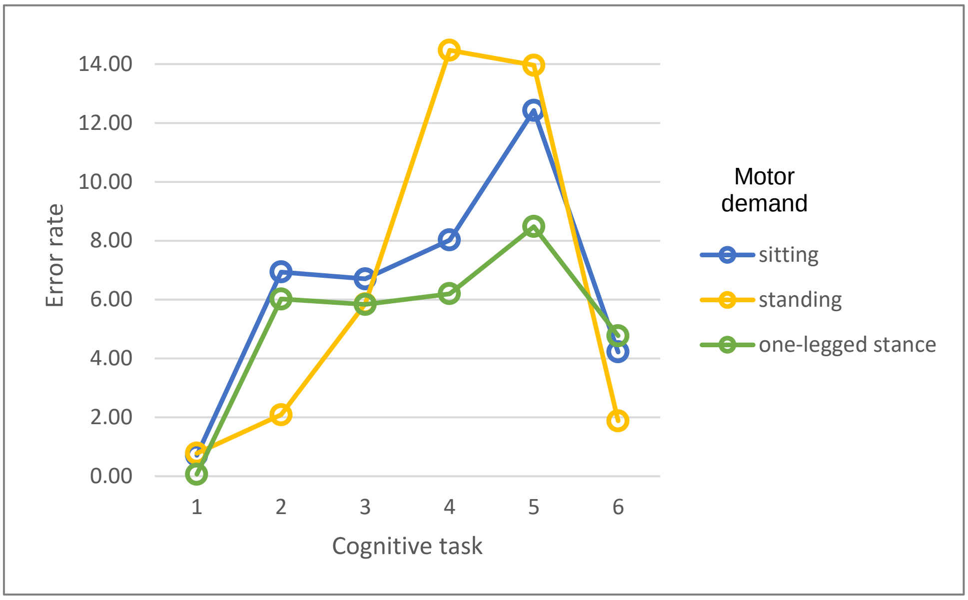


*Figure 43 Effects on motor demand*cognitive task*type [auditive] interaction in error rate.*

The interaction effect motor*cognitive task*type was analyzed in **error rate** with one-way ANOVAs for both type and motor demand with respect to the factor cognitive task (**visual**: **sitting**: F(5,275)=16.15, p<0.001*, post-hoc Scheffé: 3-2: MD=6, p<0.001, 4-2: MD=6.1, p<0.001, 5-2: MD=5.99, p<0.001; **standing**: F(5,282)=27.74, p<0.001*, post-hoc Scheffé: 2-1: MD=4.59, p=0.005, 5-4: MD=6.62, p<0.001, 6-5: MD=-6.97, p<0.001; **one-legged stance**: F(5,272)=19.99, p<0.001*, post-hoc Scheffé: 3-1: MD=6.3, p<0.001, 4-3: MD=5.72, p=0.001, 6-4: MD=-7.69, p<0.001; **auditive**: **sitting**: F(5,284)=16.66, p<0.001*, post-hoc Scheffé: 2-1: MD=6.23, p<0.001, 6-5: -8.08, p<0.001; **standing**: F(5,278)=45.12, p<0.001*, post-hoc Scheffé: 4-3: MD=8.61, p<0.001, 6-5: MD=-12.1, p<0.001; **one-legged stance**: F(5,280)=9.21, p<0.001*, post-hoc Scheffé: 2-1: MD=5.95, p=0.001, 6-1: MD=4.7, p=0.022). Finally, ANOVAs for each cognitive task yielded inconsistent results (**visual**: **cognitive task one**: F(2,133)=5.71, p=0.004*, post-hoc Scheffé: 2-1: MD=-0.33, p=0.006; **cognitive task two**: F(2,141)=14.44, p<0.001*, post-hoc Scheffé: 2-1: MD=3.82, p<0.001, 3-1: MD=3.23, p<0.001; **cognitive task three**: F(2,146)=4.34, p=0.015, **cognitive task four**: F(2,138)=8.59, p<0.001*, post-hoc Scheffé: 3-2: 5.94, p=0.001, 3-1: 5.24, p=0.004; **cognitive task five**: F(2,139)=7.46, p=0.001*, post-hoc Scheffé: 2-1: MD=6.03, p=0.001, 3-2: MD=-4.21, p=0.035; **cognitive task six**: F(2,129)=1.62, p=0.201; **auditive**: **cognitive task one**: F(2,137)=9.55, p<0.001*, post-hoc Scheffé: 3-2: MD=-0.71, p=0.001, 3-1: MD=-0.64, p=0.002; **cognitive task two**: F(2,143)=15.16, p<0.001*, post-hoc Scheffé: 2-1: MD=-4.85, p<0.001, 3-1: MD=3.93, p<0.001; **cognitive task three**: F(2,146)=0.51, p=0.601; **cognitive task four**: F(2,142)=13.53, p<0.001*, post-hoc Scheffé: 2-1: MD=6.24, p=0.001, 3-2: MD=-8.27, p<0.001; **cognitive task five**: F(2,138)=3.48, p=0.034, **cognitive task six**: F(2,133)=3.64, p=0.029.

3.2.3. Discussion

The present study aimed to provide a better understanding of the influence of cognitive task-difficulty/complexity, motor demands, the way of task-presentation, as well as the process of aging within a dual-task paradigm. The main findings of the study at hand can be summarized as follows:

- Increasing cognitive task-difficulty leads to a general increase in response time, under both single- and dual-task conditions.
- Rapid increase in response time between cognitive tasks three and four represents the influence of the kind of stimulus. While tasks one to three comprise a reaction to simple points or tones, task four to six comprise more complex contents such as letters and numbers.
- Additional mnemonic components (task 6) lead to an increase in response time, but also to a substantial decrease in error rate.
- In general, there was no significant influence of different motor demands.
- Inconsistent findings regarding the error rate. However, a tendency of decreased error rate under one-legged stance was found.
- Longer response times in the auditory compared to visual stimulus-presentation.
- Increasing age is associated with a general increase in response time of cognitive tasks under both single- and dual-task conditions.
- A pattern in response time similar among the younger groups one (aged 20-30 years) and two (aged 30-40 years), as well as the two older groups four (aged 50-60 years) and five (aged 60-80 years) was identified. On the contrary, age group three (aged 40-50 years) showed a deviant pattern, which could be partly assigned to the younger (within easier cognitive tasks) and partly to the older group (within more difficult cognitive tasks).

The present findings of an increased response time and error rate with increasing task-difficulty are in accordance with previous findings reported by Huang and Pashler (2005). Within their study, the authors reported an affected search efficiency by increasing task difficulty of visual search tasks. The authors argued that task difficulty affects efficiency of task performance but does not necessarily introduce attentional capacity limits. Regarding the rapid increase in response time between cognitive task three and four, Hancock, Williams and Manning (1995) pointed out that task performance is sensitive to multiple characteristics of the task. Considering task three and four in more detail, the relevance of the kind of reaction stimuli becomes obvious (because there are no differences in the amount of response and inhibition stimuli as well as the kind of inhibition stimuli between the two tasks). While task three comprises points with different colors / tones with different frequency, task four comprises letters and numbers. Therefore, it can be assumed that a further increase of the number of reaction and inhibition stimuli would lead to a linear increase of response time (as shown from task one to three), whereas changing the kind of stimuli to a more complex one leads to a rapid increase in response time. Further evidence for the relevance of task difficulty comes from physiological studies. In this context, Light and Obrist (1983) reported a relation between task difficulty and cardiovascular responses. Within their experiment, participants were asked to perform an appetitive reaction time task where winning money was either easy, difficult, or impossible. Similar was reported in a more recent study by Richter, Friedrich and Gendolla (2008), who indicated an increased pre ejection period and systolic blood pressure reactivity with increasing cognitive task difficulty. Considering the underlying neural mechanisms, Chen, Martinez-Conde, Macknik, Bereshpolova and Swadlow (2008) suggested that task difficulty modulates the activity of specific populations of neurons in the primary visual cortex. By contrast to the present but also other previous studies, Iwashita, McNamara, & Elder (2001) reported no interaction between task performance and task difficulty. Considering a specific phenomenon in the context of task difficulty - the rapid decrease in error rate from task five to six - one might assume that adding an additional mnemonic task might facilitate the accuracy of the primary cognitive task performance but leads to a general slowing. Thereby, it is necessary to address one question, which seems trivial but might be highly relevant in this context. To what extent can the additional mnemonic task be attributed to working or long-term memory? This question is based on the assumption that information in long-term memory would not affect additional cognitive performance, whereas holding information in working memory would highly interfere additional task performance (Watter, Geffen, & Geffen, 2001). In the present context, there are arguments for an allocation of the mnemonic component to both working memory and long-term memory. One might argue that memorizing a list of 10 words for 30 seconds would lead to a storage in long-term memory, because people would still remember some words even days afterwards. In contrast, the process of rehearsal would appear to confirm the assumption of an allocation to working memory. Assigned to the phonological loop and visuospatial sketchpad within Baddeley’s model of working memory (Baddeley, 2000; Baddeley et al., 2010), it has to be assumed that the repetition of information over and over again, would adversely affect further cognitive task performance. In the theoretical background, I suggested that it is time to break away from the black-box models of the 1970s and rather create models based on neuroscientific findings. At this point, I further suggest that it is not possible to clearly separate working memory from long-term memory, as well as define a so-called ‘magical number’ for representing working memory capacity. These aspects should be focused in future studies, whereas for the present context it should be kept in mind that independently of its allocation the processes addressed by the additional mnemonic components have been still active during the primary task performance which was indicated by differences in response time and error rate. Another aspect, which needs to be addressed in this context concerns the process of attention. Based on the present, but also on previous findings I suggest that additional tasks / demands could act as stimulus, facilitating the process of attention. In contrast to the load theory, which assumes that concurrent working memory load, impairs selective attention and increases distractor interference (e.g. Lavie, Hirst, De Fockert, & Viding, 2004), results indicated by Downing (2004) demonstrate the influence of working memory contents on the guidance of attention. While early non-human studies of macaques confirmed these findings on a single-cell level (e.g. Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993), further evidence for a facilitating effect of working memory tasks on attention in humans comes from Park, Kim and Chun (2007). Therein, within two experiments, participants were asked to perform a working memory task as well as a same / different matching task that required focusing on targets while ignoring distractors. The authors reported on the one hand, that sharing the same limited capacity processing mechanisms by working memory items and targets in the matching task leads to an increase of distractor interference. On the other hand, interference decreased and therefore target selection was facilitated when working memory items shared processing with distractors in the matching task. In case of using long-term memory for memorizing the ten words in the present context, previous findings reported that information from long-term memory is highly related to the capacity of attention and that individuals with greater attentional capacity can more readily utilize information in long-term memory to support recall (e.g. Hambrick & Engle, 2002). Furthermore, non-human studies reported that priming of attention leads to a facilitation of the process of responding (Fremouw, Herbranson, & Shimp, 1998). In sum, cumulating evidence supported the idea of attention facilitation as a possibility for the substantial decrease in error rate.

Considering the hypothesis of an increased response time and error rate with increasing demand of a simultaneously performed motor task, the present results showed no significant influence of the different motor demands on response time, and only marginal effects in the easier cognitive tasks on error rate. Instead, participants showed a trend of shorter response times in simultaneously performing the most demanding motor task, standing on one leg. Furthermore, this phenomenon was also partly revealed within the error rate. The motor demands of sitting, standing and standing on one leg are in contrast to the ones used in previous studies. Here, researchers used more demanding tasks such as walking (e.g. Woollacott & Shumway-Cook, 2002), tandem stance (e.g. Dault et al., 2001a) or a sway referenced surface (e.g. Swan et al., 2004). According to Takakusaki (2017) - who suggested automated or highly trained / learned motor functions are barely restricted to the brain stem and the spinal cord - it could be assumed that the motor demands applied in the present context might be too simple to identify any effects. In contrast, others reported dual-task associated differences also in normal standing conditions (Lajoie et al., 1993; Pellecchia, 2003). For example, Lajoie et al. (1993) revealed a significant increase in response time of cognitive task performance in normal standing, compared to sitting. In addition to the findings of Lajoie (1993), which focused exclusively on cognitive task-performance, Pellecchia (2003) reported a deterioration in motor performance of standing with increasing difficulty of a simultaneously performed cognitive task (digit reversal, digit classification, and counting backwards). In accordance with the present findings, Shumway-Cook and Woollacott (2000) reported no effects in simultaneously performing a choice reaction time auditory task while standing. Furthermore, participants in the study conducted by Mitra (2003) tended to search faster in narrow stance compared to normal stance but also swayed more with increasing search-load, and made more errors in the high search-load condition. Within their study, the authors suggested that the results are based on a sharing of limited-capacity, modality-non-specific spatial-attentional resource between postural and suprapostural tasks. In the present context, I speculate that the used motor demands lead to an attention facilitation and therefore reduce mental effort. Further support for this assumption comes from Woollacott and Shumway-Cook (2002) who stated in their review that maintaining an upright stance might tax cognitive factors, such as attentional processes.

With respect to age-related differences, participants in the present study showed a general increase in response time of cognitive task performance under both single- and dual-task conditions with increasing age. While the two younger groups (aged 20-30 years & 30-40 years) clearly differentiated between the two older ones (aged 50-60 years & 60-80 years), group three (aged 40-50 years) showed a divergent pattern. Findings at hand confirmed the previous assumption of an increased age-related dual-task cost with increasing difficulty /

complexity, as summarized in the complexity hypothesis (e.g. Hartley & Little, 1999; Mattay et al., 2002; McDowd & Craik, 1988; Salthouse et al., 1984; Wright, 1981). Further evidence for age-related differences in simple and complex reaction time tasks comes from Vaportzis et al. (2013). Within their experiment, participants showed an inverse pattern regarding response time and error rate from simple to complex tasks. The authors argued that younger and older adults use different strategies depending on complexity and difficulty. Another assumption, previously made in this context, concerns the prioritization of motor demands in motor / cognitive dual-task situations. As already reported above that motor demands are generally prioritized against cognitive tasks, this behavior becomes more and more present with increasing age, in order to maintain postural control and avoid falls (e.g. Doumas et al., 2009; Li et al., 2001). By contrast, Srygley et al. (2009) reported age-related differences in motor but not in cognitive task performance of a motor/cognitive-dual-task paradigm. Furthermore, Lajoie et al. (1996), Lindenberger et al. (2000) and Sparrow et al. (2006) indicated an age-related increase in both domains. No age-related effects were found by Springer et al. (2006) in comparing a walking task with three different cognitive tasks.

A further aspect - which might provide some explanations in this context - concerns age-related differences in executive functions (e.g. Zelazo, Craik, & Booth, 2004). While the function of inhibition is highly relevant in tasks comprising a non-responding component (as it is in task two, four, five, and six), previous findings reported impairments in higher age (e.g. Comalli et al., 1962, Williams et al., 1999). Intact working memory might be another function highly relevant in successfully performing the present tasks. Especially in the more difficulty / complexity cognitive tasks which require the memorization of the task description (which stimuli to react to and which not, but also which trigger to use), the working memory becomes more and more relevant. Therefore, with increasing the amount of different stimuli, the requirement for, regarding the working memory increases. In this context, Brennan et al. (1997) and Rönnlund et al. (2001) reported increased age-related differences with increasing task difficulty of working memory tasks. Therefore, it is not surprising that the different age groups of the present study performed nearly similar in the simple reaction task and showed greater differences with increasing difficulty / complexity. Considering the executive function of shifting, previous findings indicated a relation between the process of aging and a decline in task-shifting (Cepeda et al., 2001; Lezak, 1995; Mejia et al., 1998). Thereby, this function is important in several contexts of the present study, such as shifting between response and inhibition, the kind of response, motor and cognitive task performance. In the context of shifting between cognitive and motor tasks, the relation between more complex motor tasks and executive functions, which is frequently pointed out in previous articles (e.g. Hausdorff et al., 2005; Springer et al., 2006), needs to be considered. Based on these findings, it can be speculated that both a decline in executive functions and in more complex motor tasks adversely affect each other; especially in situations where challenging motor demands need to be performed simultaneously with complex cognitive tasks (which require a high level of executive functions). Next to executive functions, the aspect of attention and resource allocation should be additionally considered. For example, Woollacott and Shumway-Cook (2002) pointed out the relevance of increasing attentional resources for maintaining both postural control and gait in older adults. Similar was reported by Doumas et al. (2008), concerning resource allocation in sensorimotor and cognitive processing. By contrast, early findings identified no age-related differences in division of attention (McDowd & Caik, 1988; Plude & Doussard-Roosevelt, 1989). Furthermore, in their meta-analysis Verhaeghen and Cerella (2002) reported a greater dual-task cost among the elderly compared to younger adults, but could not identify age-related deficits specific to selective attention. In accordance with further studies of attentional processes among the elderly (e.g. Hartley & Little, 1999; Redfern, Jennings, Martin, & Furman, 2001), it can be suggested that the process of attention seems to play a subordinate role in explaining age-related differences in dual-task performance.

Considering the way of stimulus presentation, which must be seen as a supplementary field in the present study, participants showed significant differences between visual and auditory task presentation in both error rate and response time. Longer response times in auditory conditions can be explained by an increasing time of perception and processing of auditory compared to visual stimuli. In this context, it should be further mentioned that visually presented number (task four to six) are perceived as numbers, whereas auditory presented numbers are perceived as words. By contrast to the present findings, Carterette and Jones (1967) postulated that visual processing of information in adults is at least as good as auditory. Similar results were reported in a dual-task study by Baron and Mattila (1989) who identified a similar decrease in both visual and auditory task settings. Furthermore, Molholm, Ritter, Murray, Javitt, Schroeder and Foxe (2002) showed similar mean reaction-times in the visual (305ms) and the auditory (297ms) task setting. Focusing motor task performance, Hunter and Hoffman (2001) identified, next to a greater variability of the center of pressure in the non-cognitive condition, no differences between visual and auditory conditions. Similar was reported by Vuillerme, Nougier and Teasdale (2000) using a visual and auditory task with verbal response while standing on a force platform. In accordance with the present findings, Riley et al. (2005) showed that the spatiotemporal profile of postural sway was affected by both visual and auditory short-term memory tasks, but to a greater degree by the auditory task, which could be deduced from different computational pathways. Further evidence for the findings of differences in the way of stimulus presentation comes from Alho, Woods, Algazi and Näätänen (1992). Within their event-related potential study, selective attention tasks were used in either auditory or visual task-setting. The authors identified differences between auditory intermodal attention effects and those typically obtained during intramodal selective attention, whereas visual intermodal attention effects were similar to the effects associated with intramodal visual attention.

Next to the highly interesting findings of the present study, some limitations have to be discussed additionally. First, I have to account for not having met the assumptions for MANOVA testing that are multivariate normal distribution and homoscedasticity of the variables. On the one hand, in terms of large sample sizes due to our procedure, the probability of generating significant normality tests is increasing. On the other hand, MANOVA procedure seems to be rather robust against violations of the assumptions with large sample sizes, equal group sizes, and with increasing group number (e.g. Finch, 2005). Moreover, despite non-homoscedastic univariate data (measured by Levene-tests), I have decided to analyze the data set with the mentioned MANOVA design as in the present case (sample sizes equal, large group number) a nonparametric variant of MANOVA would not remarkably perform better (e.g. Finch, 2005). Furthermore, I am also aware that using cross-sectional designs should not be ascribed to age-related effects without considering the problems of confounding. In the present study, factors such as technical understanding, social influences, or age-related openness to the experiment etc., may be discussed. There are various ways to exclude or control confounding variables such as statistical methods, randomization, restriction or matching (Pourhoseingholi, Baghestani, & Vahedi, 2012). For the study at hand, I argue that the simple laboratory design is likely to reduce confounding effects to a minimum. Furthermore, it can be assumed that neither single longitudinal nor cross-sectional studies can interpret age-related effects without biases.

In contrast to most previous motor / cognitive dual-task studies, which focused on the motor components, dependent variables in the study at hand exclusively regard on cognitive task-performance. Based on previous findings, I argue that both older (e.g. Li et al., 2001) and younger adults (e.g. Siu & Woollacott, 2007) prioritize motor task performance in simultaneously performing motor and cognitive tasks. Therefore, I suggest that differences / impairments in motor / cognitive dual-task performance will firstly result in changes of cognitive task performance. Although, the quantification of motor demands should not be neglected, especially in the context of increasing risk of falling for example in the elderly, the cognitive tasks appear to be more sensitive. Another fact that should be mentioned is a methodological induced influence on attentional resources, which is called the focus of attention (Wulf, Höß, & Prinz, 1998). Wulf and collegues (for a review see Wulf, 2013) have shown that experimental instructions that are made to target on internal effects of a task lead to an internal focus of attention, whereas instructions making subjects concentrate on external effects of a task lead to an external focus of attention, and as a consequence, may induce different effects on the motor outcome variable. In the study at hand, I did not specify any further instructions to the motor task. It could be speculated that additional instructions that lead to an internal (‘please solve the tasks without any error but as fast as you can and try to sway as less as possible’) or external focus of attention (‘please solve the tasks without any error but as fast as you can. Try to keep the sway of the cursor in front of you which is linked to your body sway as less as possible.’) with respect to the motor task may induce a more demanding loading. Therefore, it could be assumed that in this study the additional motor tasks were limited to an automatized level (lower information processing stage), which therefore showed a minor interference with the cognitive tasks (higher information processing stage). This theory is in line with several early studies that have shown that motor tasks conducted by professionals – hence highly automatized tasks – simultaneously conducted with an additional cognitive task have a minor effect on the outcome variables, whereas the same motor tasks executed by amateurs lead to great effects (e.g. Abernethy, 1988; Smith & Chamberlin, 1992).

Despite the limitations, the present study provides some highly interested findings, which lead to the following conclusions. First, increasing the amount of different stimuli as well as possibilities to respond leads to a linear decrease in task-performance, whereas different kinds of stimuli lead to rapid changes in task-performance. Second, it can be assumed that both additional mnemonic components as well as motor demands might facilitate the focus of attention and therefore improve the performance of a primary cognitive task. Third, the present study demonstrated the influence of aging in performing different single- and dual-tasks, but furthermore highlighted the relevance of the age between 40 and 50 years as key role in transition from younger and older adults. Fourth, even among older adults, results revealed no negative effects of the additionally used sitting, standing, and one-legged stance on cognitive task performance. Fifth, task-performance clearly differed between the type of presentation because of the increased time of perception and processing of auditory stimuli and the fact that visual presented numbers are perceived as numbers, whereas auditory presented numbers perceived as words. Especially with regard to both the aging society and the increasing complexity of our everyday life, the aspects focused in the study at hand should be addressed in future studies in a further applied context.

3.3. Experiment III

Cognitive performance under different demands – Insights from a more applied perspective

Every day, we are deciding 100 to 1000 times or even more; in complex scientific, technical, economical and leadership situations, but also in almost every situation of daily living. These processes are mostly performed not isolated, but under the influence of numerous additional demands. In this context, previous studies focused the influence of additional cognitive task-performance, stress, diseases, and the process of aging (e.g. Gathmann et al., 2014a; Gathmann et al., 2014b; Pabst et al., 2013a) - as it is shown in the theoretical background - but the effects of simultaneously performing motor demands is for some reason neglected. However, both negative as well as facilitating effects in combining cognitive tasks and motor demands have been reported in various fields of interest (e.g. Swan et al., 2004; Shumway-Cook, & Woollacott, 2000) but also shown in the previous experiments. Based on these findings as well as the fact that numerous decisions are made under various motor demands, I suggest that attention should also be paid on the effects of performing additional motor tasks within decision-making processes. Therefore, the present experiment addresses the effects of simultaneously performing a motor demand and decision making under objective risk. Based on previous studies, it is hypothesized that performing decision making under objective risk with additional motor demands leads to an increase in disadvantageous behavior.

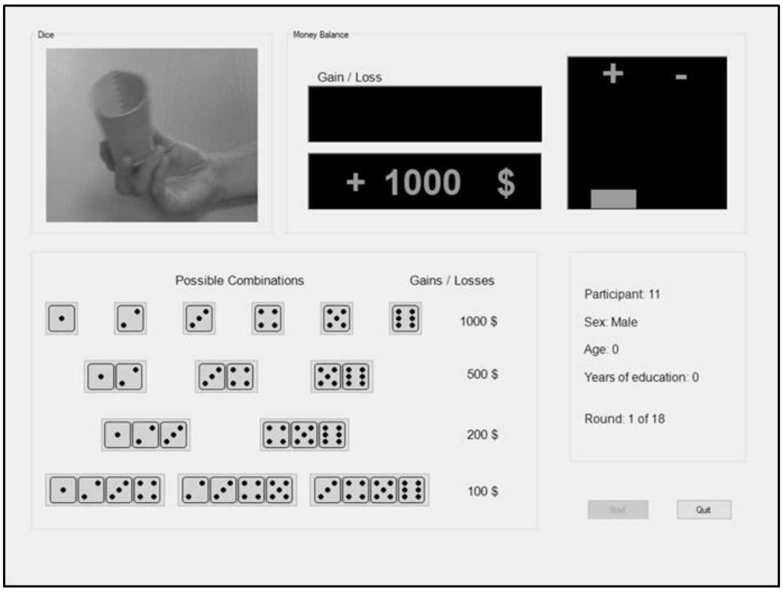
3.3.1. Material and methods

Participants

In total, 72 people participated in the present study. People were assigned either to the sitting group [36 people ranging from 19-30 years (mean age 21.44 ± 3.20 years) (28 female)] or to the one-legged stance group [36 people ranging from 18-25 years (mean age 21.17 ± 1.84 years) (25 female)]. Participants were recruited from the University Duisburg-Essen and the Hochschule Fresenius (Idstein). All participants reported normal or corrected-to-normal eyesight as well as hearing abilities and no history of neurological or psychological disorder. The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. All participants provided written informed consent prior to the experiment and were informed that they could end participation at any time without reprisal.

Stimuli

In the study at hand, the ‘Game of Dice Task’ was used to measure decision making under objective risk (Brand et al., 2005). Within the ‘Game of Dice Task’ task, the probabilities for winning are easy to comprehend and principally calculable by simple mathematic. In order to maximize a fictitious start-capital of 1.000€, participants had to decide which number of a virtual dice will be thrown next. The bet can be placed on one single number (winning probability 16.67%, related to a gain/loss of € 1,000), on two numbers in combination (winning probability 33.33%, gain/loss € 500), on three numbers in combination (winning probability 50%, gain/loss € 200) or on four numbers in combination (winning probability 66.67%, gain/loss € 100). Based on the winning probabilities, the single-number option and the combination of two numbers are associated with disadvantageous or high-risk decisions (expectation of 1000€ * 1/6 + (-1000€) * 5/6 = -666.67€ and of 500€ * 2/6 + (-500€) * 4/6 = -166.67€ respectively), whereas the combination of three- and four-number must be seen as more advantageous or rather low-risk decisions (expectation of 200€ * 3/6 + (-200€) * 3/6 = 0€ and of 100€ * 4/6 + (-100€) * 2/6 = 33.33€ respectively). Choosing the opportunity of three numbers would statistically lead to a positive final balance and is therefore neither advantageous nor disadvantageous. During the 18 trials, the actual capital is shown constantly and the current win/loss appears on the screen after each trial (Figure 44).



Participant: 11

Sex: Male

Age: 0

Years of education: 0

Round: 1 of 18

Figure 44 The Game of Dice Task (Brand et al., 2005).

While this feedback enables participants to reconsider his/her behavior, it should be mentioned that the optimal strategy for a long-term profit is to choose four numbers in all trials (expected value for each trial: 33.33€). Accordingly, the other options do not lead to a long-term profit (expected value for one number: -666.67€, two numbers: -166.67€, three numbers: 0€).

The ‘Game of Dice Task’ was performed either while sitting in a chair (group 1) or while standing on one leg (group 2). Choosing the two different motor demands was inspired by previous findings who reported affected primary task performance by increasing the difficulty of additional motor demands (e.g. Lajoie et al., 1993).

Procedure

Before starting, participants gave informed consent after having carefully read the instructions. They were informed that they should maximize their fictitious start-capital of 1.000€ during 18 trials by choosing which number of a virtual dice will be thrown next. Furthermore, examples of the possibilities to bet were shown. In group one, participants were additionally instructed to focus the cognitive and the motor task equally. The ‘Game of Dice Task’ was presented on a commercial screen, set at eye level of the participants. The position of the chair, the screen, as well as the standing position were standardized and cross-marked to ensure equal conditions for all participants. Within each trial, participants gave their response verbally to the experimenter and get their feedback directly on the screen. The total duration of the experiment was 10 minutes.

Data Analysis

All statistical analyses were carried out with Statistical Package for the Social Sciences version 21.0 for Windows. Normal distribution of the data was tested with the Shapiro-Wilk-Test and homogeneity of variance with the Levene-Test. T-tests for independent samples were used to analyze between-group differences in age and for comparing GDT net scores and final outcome (in €) of the two groups. GDT net score was calculated by subtracting the number of risky selections from the number of safety selections. Furthermore, a two-way analysis of variance with repeated measurements with ‘choice’ as within-subject factor and “group” as between-subject factor was used to analyze the effects of additional motor demands, on the absolute frequencies of decisions for each alternative (single number, 2, 3, or 4 numbers together). Alpha error was set at 0.05. Results were corrected for multiple comparisons (Bonferroni) when appropriate.

3.3.2. Results

The groups did not differ in age (T = 0.451; df = 70; p = 0.653) and gender (25 females in the sitting and 28 females in the one-legged stance group). The GDT net score in the one-legged stance group (5.11 ± 9.28) was significantly lower (T = -4.559; df = 70; p < 0.001), than in the sitting group (13.17 ± 5.14) (Figure 45), whereas the final outcome (SI: 816.67±1,399.49; OLS: 583.33±2,568.43) did not differ between the two groups (T = 0.634; df = 70; p = 0.634).

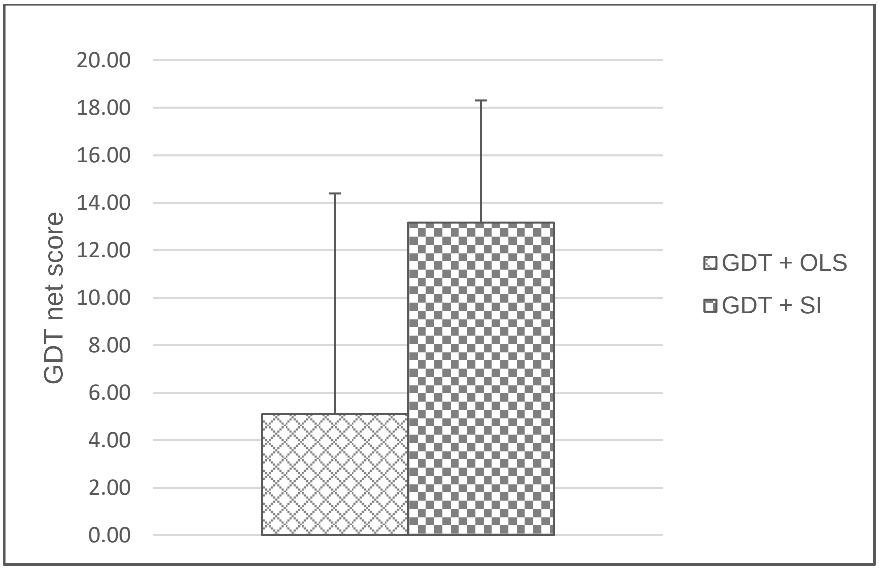


Figure 45 Netscore of the Game of Dice Task.

Considering the ANOVA outcome, there was a significant main effect for ‘choice’ (F = 31.810; p < 0.001), as well as a significant interaction of ‘choice’ X ‘group’ (F = 8.324; p = 0.001). Furthermore, people standing on one leg, more frequently selected the most disadvantageous choice (one single number), whereas the sitting group most often selected the advantageous combination of four numbers (Figure 46).

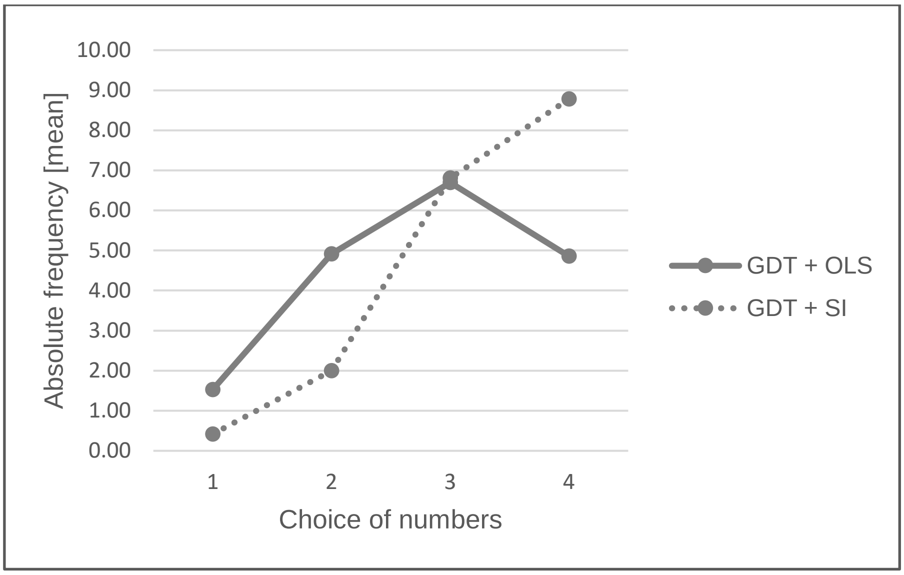


Figure 46 Absolute frequency of choice of numbers.

Between-group comparisons of selection frequency of each single alternative revealed significant differences for ‘single number’ (OLS: mean = 1.53, sd = 2.36; SI: mean = 0.42, sd = 0.91; p = 0.010), two numbers (OLS: mean = 4.92, sd = 3.61; SI: mean = 2.00, sd = 2.18; p < 0.001), and four numbers (OLS: mean = 4.86, sd = 4.29; SI: mean = 8.78, sd = 6.00; p = 0.002), whereas the frequency of three numbers (OLS: mean = 6.69; sd = 3.08; SI: mean = 6.81; sd = 4.53; p = 0.904) did not differ between the two groups.

3.3.3. Discussion

The main findings of the present study indicated that participants perform more disadvantageous in the Game of Dice Task when standing on one leg, compared to sitting. While O’Brien and Ahmed (2014) reported no differences in performing an economic decision task while standing or sitting, previous Game of Dice Task studies are in accordance with the findings at hand. Within these studies, the authors reported an increased disadvantageous behavior under dual- compared to single-task conditions (Gathmann et al., 2014a; Gathmann et al., 2014b; Gathmann et al. 2015; Pabst et al., 2013b; Starcke et al., 2011a; Verbruggen et al., 2012). For example, Starcke et al. (2011b) argued that occurring interferences are based on the fact that both the Game of Dice Task and an additional working memory task compete for existing resources of the rational-analytical system two. Further evidence for this assumption comes from both single Game of Dice Task (e.g. Brand et al., 2009a) as well as single working memory studies (e.g. Evans, 2003; Oppenheimer, 2008 for an overview). Considering the Game of Dice Task, it is argued that the attribution to the rational-analytical system is based on the characteristics of explicit rules for gains and losses as well as task contingencies (Brand et al., 2009a). In the context of the working memory, studies pointed out the necessity of the rational-analytical system (Evans, 2003; Oppenheimer, 2008). Based on these findings, it can be assumed that additional working memory load leads to a greater involvement of system one in performing the Game of Dice Task and therefore to an increasing disadvantageous behavior. This is in accordance with Hinson, Jameson and Whitney (2003) who reported that limits on working memory function are predictive for a more impulsive decision-making style. Within their study, participants were asked to make delay-discounting judgments under different working memory load conditions. Although standing on one leg will not require additional working memory capacity, I speculate that the motor demand also leads to an increasing relevance of system one, within performing decision making under objective risk. This assumption refers inter alia on the hypothesis of somatic marker. Described to refer to the collection of body-related responses that hallmark an emotion (Damasio et al., 1996; Bechara, & Damasio, 2005), it can be assumed that somatic markers affect the process of decision making. Furthermore, associations of rapid heartbeat but also somatic reactions from the streaked muscles (e.g. extremities, faces) play a highly relevant role in this context (Bechara, & Damasio, 2005). In the present study, I do not suggest that standing on one leg affects heart rate of younger adults, but it seems more plausible that different somatic reactions occur due to the streaked muscles in the one-legged stance compared to the sitting condition. An emotionally induced shift of decision-making strategy as proposed in the present context was also demonstrated by Figner, Mackinlay, Wilkening and Weber (2009), using a cold and a hot version of the Columbia Card Task. Participants in the hot version used ‘gut level’ and ‘excitement’ strategies, whereas in the cold version ‘mathematical’ processes were mostly engaged. Another aspect in the context of the intuitive and reflective systems comprises stress. Starcke et al. (2008) for example reported a significantly lower performance of the Game of Dice Task under stress, but also a correlation between decreased task-performance and increased level of cortisol. Within a further study of the research group (Starcke et al., 2011a), the authors confirmed their previous results, by reporting a positive correlation of cortisol level and egoistic decision making in emotional dilemmas. These findings are in accordance with numerous other studies, which addressed the effects of stress in various fields of decision making (e.g. Gathmann et al., 2014a). Within the present study, I assume that the motor component of standing on one leg might additionally act as stressor and therefore triggers a shift from reflective to more intuitive decision making (reflected in a more disadvantageous behavior).

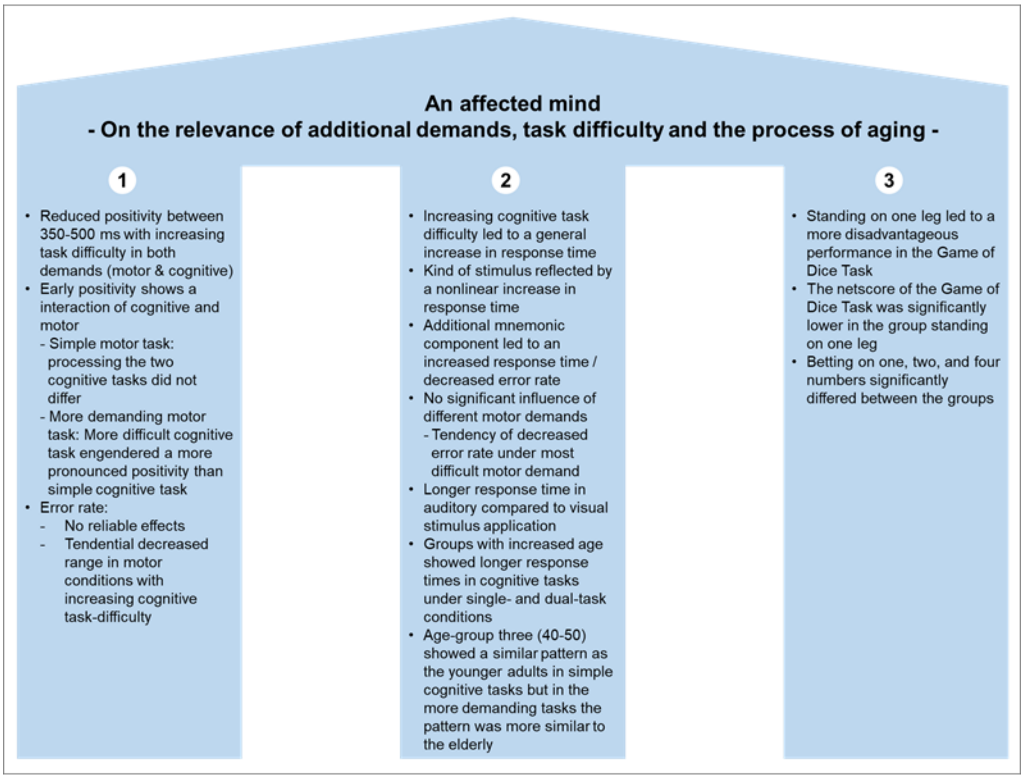
Along with the stated aspects, cognitive abilities should be discussed in the context of changing decision-making strategies. For example, West and Stanovich (2003) showed that decision makers with a higher cognitive performance chose the most rational maximization strategy. Furthermore, the authors reported more advantageous decisions in the Game of Dice Task in participants who tended to make more calculations. Regarding the influence of motor demands on cognitive abilities, Ouchi, Okada, Yoshikawa, Nobezawa and Futatsubashi (1999) reported increased cerebral blood flow in the cerebellar anterior vermis and the posterior lobe lateral cortex ipsilateral to the weight-bearing side in participants who stood on one leg. Therefore, it can be speculated that in situations where the available cognitive resources for decision making under objective risk were reduced, for example by adding additional motor demands, the impulsive system becomes more prominent. Considering dual-task performance in the Iowa Gambling Task, which is assumed to tap more in the impulsive system, Turnbull et al. (2005) found no differences in Iowa Gambling Task performance between single- and dual-task conditions. Within their study, the authors used two different secondary tasks, an executive and a non-executive task.

Finally, the role of executive functions should be additionally considered in this context. Here, numerous studies in various fields (e.g. Bull, Phillips & Conway, 2008), but also in the context of decision making (e.g. Toplak, Sorge, Benoit, West, & Stanovich, 2010) previously investigated the influence of executive functions. Especially in decision making under objective risk, executive functions are discussed as main components for guiding development and applying decision-making strategies, as well as feedback processing (Brand et al., 2005; Brand et al., 2006; Brand et al., 2007b; Brand et al., 2008; Brand et al., 2009a; Euteneuer et al., 2009; Schiebener et al., 2011; Schiebener et al., 2012; Schiebener et al., 2013; Schiebener et al., 2014). For example, Gathmann et al. (2015) asked their participants to simultaneously perform the Game of Dice Task and a n-back task. Furthermore, the authors applied the Modified Card Sorting Test as well as the Balanced Switching Task. Results demonstrated an important role of the executive function of monitoring. Until now ‘monitoring’ has not been considered in more detail, because I suggest a classification of this function as component of each of the three mostly used executive functions inhibition, updating working memory, and shifting (see also Packwood et al., 2011). Further evidence for the relevance of considering executive functions in the context of decision making under risk comes from Brand and Schiebener (2013). Based on their findings, the authors reported age-related differences only in older adults who showed decreased executive functions, but not in the elderly who performed well on executive function tasks. Regarding the study at hand, the relation between more complex motor tasks and executive functions should be additionally considered (e.g. Ble et al., 2005; Persad et al., 1995; Springer et al., 2006). In this context, Persad et al. (1995) identified problem solving, response inhibition but also attentional aspects as predictors responsible for successful obstacle avoidance. Using the trail-making test, which is described to measuring visual attention and task switching, Ble et al. (2006) suggested that in non-demented elderly executive functions are associated with tasks of lower extremity function. Focusing on the executive function of inhibition, participants in the study conducted by Springer et al. (2006) performed a stroop test and go-/nogo task next to a dual-task walking task. Here, the authors pointed out the ability of the executive function as factor for differentiating between fallers and non-fallers.

While the study at hand investigated younger adults, further research should also address age-related differences. Based on the aspect of fear of falling the influence of stress might become increasingly relevant within this group. In sum, the present study revealed that performing the Game of Dice Task while standing on one leg causes in a more disadvantageous decision-making behavior. The findings further support the increasing relevance of the impulsive system one in dual-task decision making under objective risk as well as the role of additional motor demands as mediating peoples decision making. While most decisions in everyday life have to be made under the influence of motor demands, future studies should address further more complex motor demands, such as walking.

4. General Discussion / Conclusion

The three experiments comprised in the thesis at hand investigated the influence of additional demands, task difficulty and the process of aging on cognitive task performance. The first experiment investigated a limited number of different task-combinations from a neurophysiological perspective. Additional behavioral results indicated no reliable effects neither of task-difficulty nor of additional demands. By contrast, event-related potentials showed a reduction of a positivity between 350-500 ms after stimulus onset with increasing task complexity in both demands (motor & cognitive). Furthermore, a cognitive x motor interaction was identified in the earlier positivity. Here, only the more demanding motor task revealed a differentiation between the two cognitive tasks. Within the second experiment, the number of cognitive tasks as well as motor demands was increased and further aspects such as the process of aging and the way of stimulus presentation were added. Behavioral results pointed out the relevance of cognitive task difficulty as well as the kind of stimulus in dual- but also single-task performance. Furthermore, older adults showed longer response times in cognitive tasks under both single- and dual-task conditions. Considering the influence of additional motor demands, there were no significant differences between the three motor demands regarding the response time, but a tendency of decreased error rate under the most difficult motor demand. By contrast, the third experiment highlighted the influence of performing more difficult motor demands while making decisions under objective risk. Participants performed significantly more disadvantageous in the Game of Dice Task while standing on one leg compared to the sitting condition (see Figure 47 for an overview of the findings of the three experiments).



An affected mind
- On the relevance of additional demands, task difficulty and the process of aging -

1

- Reduced positivity between 350-500 ms with increasing task difficulty in both demands (motor & cognitive)
- Early positivity shows a interaction of cognitive and motor
  - Simple motor task: processing the two cognitive tasks did not differ
  - More demanding motor task: More difficult cognitive task engendered a more pronounced positivity than simple cognitive task
- Error rate:
  - No reliable effects
  - Tendential decreased range in motor conditions with increasing cognitive task-difficulty

2

- Increasing cognitive task difficulty led to a general increase in response time
- Kind of stimulus reflected by a nonlinear increase in response time
- Additional mnemonic component led to an increased response time / decreased error rate
- No significant influence of different motor demands
  - Tendency of decreased error rate under most difficult motor demand
- Longer response time in auditory compared to visual stimulus application
- Groups with increased age showed longer response times in cognitive tasks under single- and dual-task conditions
- Age-group three (40-50) showed a similar pattern as the younger adults in simple cognitive tasks but in the more demanding tasks the pattern was more similar to the elderly

3

- Standing on one leg led to a more disadvantageous performance in the Game of Dice Task
- The netscore of the Game of Dice Task was significantly lower in the group standing on one leg
- Betting on one, two, and four numbers significantly differed between the groups

Figure 47 Overview of the findings of the three experiments.

While the findings of the single experiments have been already discussed in the respective studies, the chapter at hand aims a classification of these within existing models and theoretical aspects. At the beginning of this thesis, I stated the aspect that our brain cannot process all information it is confronted with. This became apparent in complex but also simple tasks. In course of the three experiments, a broad variety of cognitive tasks from simple reaction time tasks to dichotomous choice and double inhibition tasks with additional mnemonic components, but also more applied tasks in the form of a gambling task were used. In accordance with Atkinson and Shiffrin (1968) - but also more recent studies (e.g. Pashler, 1994) - the present findings of the three experiments indicate that processing more novel information or information that require a higher amount of controlled processes lead to greater interferences in dual- but also single-task situations. Although the tasks of the first and second experiment are not commonly practiced, the used stimuli of numbers and letters are omnipresent in everyone’s daily life. By contrast, the Game of Dice Task constitutes a noval - in some ways relatively complex - task. In this context, previous neurophysiological studies highlighted the increasing demand of the performance of novel and more difficult tasks compared to overlearned ones by indigating an increased activity in the prefrontal and anterior cingulate cortex (e.g. Birnmoim, 2003; Büchel et al., 1999; Frith et al., 1991; Jansma et al., 2007; Raichle et al., 1994). Another explanation was stated in some early works of Sternberg (1966) and Sternberg (1975), who assumed that more difficult / complex tasks require a greater amount of search through the memory set and thus lead to longer response times and greater interferences. Based on the present but also previous findings I modified the ‘stage theory model’ - stated by Atkinson & Shiffrin (1968) - to ensure a classification of the results at hand but also to highlight some aspects relevant in this context (Figure 48).

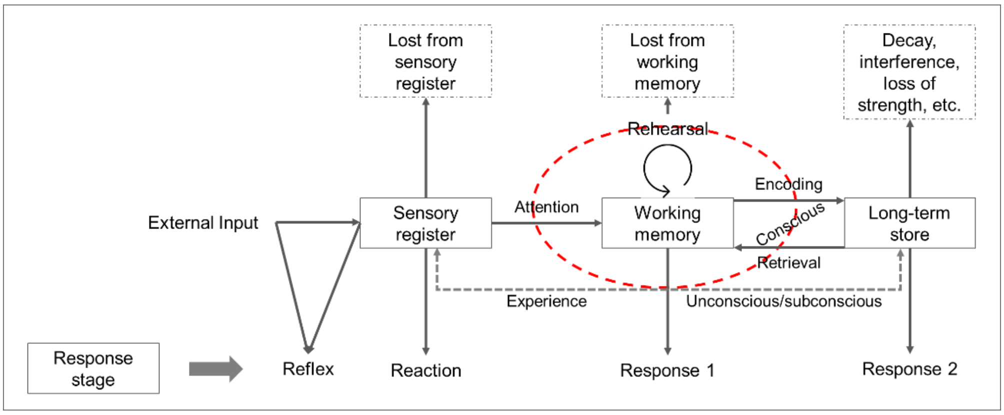


Figure 48 Modified model of Atkinson & Shiffrin (1968).

Within the modified model, I included the ‘stages of response’ to describe the kind of responses that can arise at different stages of information processing and to highlight the effects of simultaneous task performance at different stages of information processing. In advance to the first stage I stated the aspect of reflexes within the modified model, acting on a minimum level of information processing. Generally described as involuntary and nearly instantaneous (Purves & Augustine, 2004), in the present context reflexes need to be differentiated between spinal reflexes who act on a spinal level and those who act on a (lower) cortical level. For example, the pattelar reflex but also the spinal cord pattern generator (Dietz, 2003) can be summarized under the term of spinal reflexes acting without cortical involvement. Therefore, the amount of information that need to be processed in this kind of reflexes is assumed to be at the lowest level. By contrast, reflexes such as preventing a fall after stumbling require cortical activity and thus discussed in context of the sensory register. In dual-task settings, the execution of spinal reflexes is assumed to be independent of the difficulty of the secondary demand, whereas cortical reflexes are affected by simultaneously performing additional tasks. In this context, cortical relexes can be classified comparable to reaction tasks, with one exception: reflexes constitute responses to unexpected events, whereas reactions occur on expected stimuli. In the present context, the first cognitive task of the second experiment (pressing a button when a dot or tone is presented) represents a typical reaction task. By contrast to the present findings - which revealed no differences between singl- and dual-task performances on the execution of the reaction task - Herath et al. (2001) identified significant differences. In their study, participants had to respond to blunt, painless stimuli by pressing a button. While Herath et al. (2003) asked their participants to react on blunt, painless stimuli while performing additional cognitive tasks, the experiment at hand comprised different cognitive tasks and motor demands in which participants had to respond only to cognitive stimuli.

In the context of simultaneous task performance, the next stage of the model and its related aspects of attention, rehearsal as well as encoding and retrieval are of particular importance. Here, I replaced the term short-term memory with working memory. While theoretical aspects, behavioral and neurophysiological findings of the working memory are highlighted in detail in the theoretical background, its relevance in the present experiments can be seen as follows: in context of the Game of Dice Task, previous studies described a correlation between task performance and working memory capacity (e.g. Euteneuer et al., 2009). Across the first and second experiment, the working memory must be seen as indispensable for keeping task-information in mind. Here, the increasing complexity / difficulty of the tasks - as highlighted by using the example of graph theory - constitutes the increasing demand on working memory until the information is transferred into long-term memory and thus becomes increasingly automated. This aspect - of repeating information and automatization - was already highlighted in previous studies: for example in the context of reading (Schneider et al., 1984), but also relatively complex tasks such as shadowing spoken language while playing the piano (Allport, Antonis, & Reynolds, 1972), writing dictated words while reading a novel (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980) or shadowing a text while typewriting (Shaffer, 1975). More recent studies discussed the performance of walking and standing as highly automated and thus not interrupted by additional tasks. As shown across the theoretical background, findings in this context are highly inconsistent (Dault et al., 2001a/b; Lajoie et al., 2003; Maylor et al., 2001; Mitra, 2003; Pellecchia, 2003; Ramenzoni et al., 2007; Shumway-Cook & Woollacott, 2000; Vuillerme et al., 2000). By contrast, there is a general agreement that during the process of aging increasingly automated processes become more and more controlled (e.g. Beurskens & Bock, 2012; Riby et al., 2004; Verhaeghen et al., 2003). In the second experiment, older adults showed a reduced cognitive task performance but no differences in dual-task performance. In this context, I argue that the most difficult motor demand of standing on one leg - used in the present context - was too easy to reveal differences on a behavioral level. Within a pilot study - which is not part of this thesis - the design of the second experiment was transferred to a small group of people with multiple sclerosis but also healthy controls (Liebherr et al., 2017). The descriptive results showed increasing dual-task costs in people with multiple sclerosis, even under the motor demand of ‘normal’ standing compared to healthy controls. Based on these results and the fact that the mean age of the oldest group within the second experiment was 69.6±6.6 years, it can be assumed that increasing age and thus a concomitant progress of degenerative processes would also lead to increasing dual-task costs. Here, a decline in working memory capacity during the process of aging is frequently discussed - responsible for the increasing amount of interferences in simultaneously performing two tasks among older adults (e.g. Brennan et al., 1997; Park et al., 2002; Rönnlund et al., 2001). Along with this, the aspect of working memory training should be additionally considered. Based on previous findings, it can be assumed that working memory training would generally lead to a reduction of interferences in simultaneous task performance (e.g. Constantinidis & Klingberg 2016; Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012). For example, McKendrick, Ayaz, Olmstead and Parasuraman (2014) reported decreased proactive interferences, increased neural efficiency, reduced mental workload for stimulus processing, and increased working memory capacity after a working memory training. Furthermore, the effectiveness of working memory training is also reported among older adults (e.g. Borella, Caretti, Riboldi, & De Beni, 2010; Buschkuehl et al., 2008).

Along with the association of automated processes and long-term memory, further aspects such as experience but also impulsivity and reflexivity need to be highlighted in this context. While Atkinson and Shiffrin (1968) proposed no possibility of transfering information directly into the long-term memory, the modified model at hand suggest two ways: a transfer of conscious information from working memory and the possibility to transfer information unconsciously / subconsciously direct from the sensory register. Here, the aspect of experience might play a relevant role. For example - think about driving a car - an experienced driver can roughly estimate when driving 60 mph, without looking at the speedometer. This phenomenon does not base on the fact that every time we drive 60 mph, we consciously think about how it feels to drive this speed and repeat this feeling as long as we memorized it into long-term memory. It is rather based on our experience, which grows un- / subconsciously. This aspect is also frequently discussed in the context of the impulsive and reflective system (e.g. Kahneman, Lovallo, & Sibony, 2011). While it is pointed out at different places of this thesis, there is an ongoing debate whether a clear separation between the two systems can be made or not. In accordance with Schiebener and Brand (2015), I suggest that both systems guide humans behavior in pararell but one has the upper hand; which one depends on several individual and environmental aspects, as well as the situation itself. In the present context, I highlighted the somatic markers but also the aspect of stress relevant for shifting between the two systems in dual-task situations. This is reflected in a more disadvantage decision making behavior of the Game of Dice Task while standing on one leg. Another aspect frequently used for explaining differences in dual- compared to single-task performance comprises attention. In the modified model at hand, attention is adopted from the original model in the context of transferring information from the sensory register to working memory. Furthermore, Kahneman (1993) proposed that attention can selectively act at multiple stages of information processing and is amongst other contributors responsible for the limitations in information processing (Kahneman, 1993). The relation of attention and automaticity in information processing was described by Logan (1988), who stated that the degree of automaticity rather than resource limitations moderates the effects of attention in information processing. The aspect of allocation of attention during automatic processing was also highlighted by Strayer and Kramer (1990) in the context of the event-related potential P3/300. Furthermore, both the P3/300 and the P2/200 are frequently described as reflecting the consequences of paying attention to a stimulus, dividing attention between different stimuli or drifting ones attention away (e.g. Hillyard, 1981; Hillyard & Kutas, 1983; Hillyard et al., 1978; Johnson, 1988; Maeno et al., 2004). Further neurophysiological studies highlighted the relevance of the parietal and frontal lobe but also the mid-brain in switching attention between different tasks / demands (Posner and Raichle, 1994; Sylvester et al., 2003). Based on these findings, the increased amplitude in the earlier positivity - predominantly located at the parietal electrodes - from easy to more difficult cognitive tasks, can be interpreted as follows: standing on one leg facilitates the process of paying attention on the more difficult cognitive task. Similar was reported in a behavioral study by Kathmann et al. (1999), who found a reduced error rate when attention was divided between two tasks. By contrast, Siu et al. (2008) reported a diminished attention in the stroop task under dual- compared to single-task conditions. Among older adults, previous studies explained an increase in dual-task costs by a decline in attentional resources (Hauer et al., 2003; Lajoie et al., 1996; Woollacott & Shumway-Cook; 2002). Although the aspect of attention is stated in the modified model in the context of transferring information from sensory register to the working memory, I agree with Kahneman (1993) that this aspect plays a highly relevant role at every stage of information processing.

Considering the stages of response again, it is assumed that both the similarity between stimulus and response but also the instruction - what to focus on - might play a highly relevant role. Regarding the instruction of task-focusing, participants across all three experiments were asked to focus on both task performances equally. In this context, Mitra and Fraizer (2004) reported differences in error rate depending on whether the instruction was to focus both tasks equally, or to focus on the performance of one task predominantly. Similar findings come from Schumacher et al. (2001), who showed that observed interferences can be modulated by instructions of task prioritization. Regarding the influence of stimulus / response similarity, cross talk models assume that greater similarity leads to increased interferences, as highlighted in the theoretical background (e.g. Koch, 2009; Navon and Miller, 1987). While most dual-task studies used a manual way of responding (e.g. Tombu & Jolicœur, 2002), some studies combined visual stimuli with verbal responding (Dux et al., 2006) but also auditory stimuli with verbal responding (Bowen, Wenman, Mickelborough, Foster, Hill & Hill, 2001). Based on previous findings of cross talk models, it can be assumed that the combination of auditory stimuli and verbal responding lead to higher interferences compared to other stimulus / response combinations. While this topic should be addressed in further studies, the present experiments exclusively used either a visual / manual, auditory / manual, or visual / verbal stimulus / response combination in order to avoid similarity effects. Along with the limitations of each study, the effects of additional demands, task difficulty and the process of aging were investigated across the three experiment only in consideration of cognitive task performance without investigating the motor component. Furthermore, a higher number of cognitive tasks as well as an increasingly number motor demands - as implemented in the second experiment - should be additionally investigated from a neurophysiological perspective. Based on technical innovations, social pressure but also our own expectations the amount of factors that affect our mind positively but also negatively, will constantly increase. Therefore, additional and more demanding motor conditions, further cognitive tasks with higher difficulty /complexity but also increasingly real-world scenarios should be addressed within future research of this field.

The present thesis will be completed by addressing the discussion of the existence of a central bottleneck or the possibility of sharing capacity between different tasks / demands. From a behavioral point of view, Schumacher et al. (2001) reported the possibility of perfect time-sharing in dual-task performance of basic choice reaction tasks even after a relatively modest amount of practice. In accordance, Tombu and Jolicœur (2005) confirmed the assumption of a central capacity sharing, which divides resources amoung to-be-performed tasks. By contrast, results presented by Ruthruff, Pashler and Klaasen (2001) confirmed the assumtion of structural central bottleneck models. Furthermore, Dux et al. (2006) suggested a neural network of frontal lobe areas, which acts as a central bottleneck responsible for severely limits of our ability to multitask. While the stated findings are based on the combination of two reaction / response tasks, the experiments in the manuscript at hand comprised one reaction / response task and an additional demand that requires no direct response. Nevertheless, based on previous behavioral and neurophysiological studies but also the present findings, I suggest that we should no longer deal with the discussion about the two theories, but rather investigate dual-task situations – similar to the approach of the thesis at hand – from an increasingly systematic point of view. Here, I assume that the difficulty / complexity of single tasks but also the discussed factor of task and stimulus / response similarity plays a highly relevant role and thus should be considered from basal stimuli to more applied tasks.

Although humans’ ability of simultaneously performing different tasks / demands is one of the most fascinating aspect in numerous fields of science, in daily life we should no longer strive for performing as many things as possible at the same time, but rather prioritize single aspects such as drinking a glass of wine with some friends without focusing additional demands.

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Declaration in Lieu of an oath

I hereby declare in lieu of an oath that I have completed the present thesis entitled ‘AN AFFECTED MIND - On the relevance of additional demands, task difficulty and the process of aging –‘ indpendently and without illegitimate assistance from third parties. I have use no other than the specified sources and aids. All the passages taken literally or meaningfully from others have been made recognizable as such. The thesis has not been submitted to any examination board in this, or similar form.

Duisburg, den 26.10.2017

Magnus Liebherr, M.Sc.