Individual Differences in Working Memory

Investigating the Influence of Cognitive Control

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List of Papers

This doctoral dissertation is based on the following studies:

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2. Hiebel, N, & Zimmer H.D. (2015). Individual differences in working memory capacity and attentional control. *Canadian Journal of Experimental Psychology, 69*, 17-27.

In order to guarantee a smooth reading the respective passages are not marked in the text. Furthermore, in keeping with the practice of these articles, I constantly employ “we” instead of “I”.

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List of Abbreviations

°	Degree
€	Euro
ε	Greenhouse Geißer correction
η_p^2	Effect size for ANOVAs with repeated measurements (partial eta squared)
µV	Microvolt
AB	Attentional Blink
ANOVA	Analysis of Variance
ANCOVA	Analysis of Covariance
CDA	Contralateral-delay activity
cf	Compare
CNV	Contingent negative variation
D	Distractor
EEG	Electroencephalography
e.g.	For example
ERP	Event-related potential
F	Test statistic from F distribution
i.e.	Id est (meaning that is to say)
M	Mean
ms	Millisecond
MOT	Multiple Object Tracking Task
NSW	Negative slow wave
p	Probability of equally extreme test statistic, given null hypothesis is true
r	Pearson product-moment correlation
RT	Reaction Time
SD	Standard Deviation
sec	Seconds
SOA	Stimulus onset asynchrony
STM	Short-term memory

T	Target
TBRS	Time-based resources sharing approach
vs	Versus
WM	Working Memory
WMC	Working Memory Capacity

Abstract

The amount of information a person can store for a certain time is highly limited. This limitation is known as the capacity of working memory (WM). The average capacity in the visual domain is assumed to be around four items. However, several studies found WM capacity to vary substantially among healthy young adults. The main aim of the current work was to disentangle causes underlying individual differences in WM. In five experiments we explored whether individual variations in WM are reflective of differences in selective attention.

The main purpose of Experiments 1 and 2 was to evaluate whether individuals with high and low WM capacity differ in the efficiency and speed of allocating attention on targets. We realized different versions of a cued categorization task in which different types of attention control were necessary, a more automatically triggered allocation of attention and a voluntary initiation of attention engagement. We further manipulated the inter-stimulus interval (SOA) between cue display and target presentation in order to look for differences in the latency of attention control. The results revealed that participants with low WM capacity were less effective in engaging voluntary attention control processes and they were also slower in doing so compared to high WM capacity individuals (Experiments 1 and 2). However, all trials were presented in a mixed order, so that for each trial the appropriate attention control processes have to be coordinated and constantly adapted in correspondence to the current task demands. This requires coordinating changing task demands according to the current task set – a cognitive process which is called cognitive flexibility – such as engaging attention onto targets. When the trial structure did not require such coordination processes (like on single blocks) smaller individual differences related to variations in WM capacity in the time dependent efficiency of voluntary attention control were found (Experiment 2). The interpretation that individual variations in WM capacity might not exclusively depend on the voluntary engagement of attention but also on the efficiency of cognitive flexibility was supported by further results of Experiment 1 revealing a relationship between WM capacity and indices of executive control, in particular solving competition between various processing requirements. Thus, individual variations in WM capacity seem to be related to the ability to orient attention and to flexibly coordinate the competition between changing task demands.

We further developed this idea by investigating how the ability to orient attention and the efficiency to reconfigure task sets both contribute to optimal WM functioning. As WM has a very limited online capacity it is of considerable importance for the individual to control how many, and which, items are encoded into WM, a process known as gating. One way of testing the effect of gating on WM capacity is to implement distractor-present trials in a change detection paradigm. Although gating is typically considered to be reflective of selective attention, we believed gating to be a function of both the ability to coordinate and reconfigure changing task demands and selective attention, respectively. That is, the trial structure in a change detection paradigm with distractors added typically demands the coordination of two different task sets and individuals need to continuously switch back and forth between tasks where all items, or only a subset of items (distractor-present trials), are targets. In order to examine whether effective gating is a function of processes associated with the efficiency of cognitive flexibility and selective attention we tried to disentangle both processes in some of the trials. In the standard change detection task with distractor-present trials the actual task set can first be identified when the-to-be memorized stimuli are present. Only at this point participants are able to discriminate between trials where selection processes are relevant or not. Thus, the timing of task set reconfiguration strongly depends on the distractors' presence itself and its detection. In Experiments 3 to 5, we aided task set reconfiguration processes by displaying the cue in the target color, indicating that distractors would be present, while in other trials, the cue did not reveal the current task set. In Experiments 4 and 5 we additionally realized single distractor-present blocks. Overall, participants with low WM capacity performed better in distractor-present trials when the task set could be anticipated in advance either due to the predictive task set cue or due to task context (single distractor blocks). Furthermore, and more importantly, the magnitude of this improvement and the efficiency of early selection mechanisms were both associated with the amount of available cognitive resources (Experiment 3 vs. Experiment 4).

Taken together, our results of this work contribute to a deeper understanding of the nature of individual differences in WM. Collectively, our findings suggests that there is a tight relationship between attention and WM, which is associated with a broad class of cognitive processes, reflecting the diverse modes of operation within each of these systems. The amount of consumed processing resources and the ability to resolve conflicts between competing processes seem to be important characteristics in this

multifaceted relationship. Consequently, optimal WM functioning for low WM capacity individuals might be achieved by telling individuals on what process they should allocate resources to.

Part 1

Working Memory

1 Introduction into Working Memory

1.1 The Concept of Working Memory

In our daily life we need to keep certain pieces of information in mind until the opportunity to use them arrives. Typical situations are for example going for grocery shopping with a shopping list in mind, remembering a phone number until dialing it or working out a tip in one's head in a restaurant. Another common example is reading comprehension. In order to understand a sentence, one must hold the beginning of a sentence in mind and continuously put its fragments together while reading the rest of a text. In all these situations, it is essential to hold previous information active and process new information simultaneously. Working memory (WM) is the system responsible for this. It is a key cognitive function that enables us to temporarily maintain information in an accessible state so that it may be manipulated and further processed (Baddeley & Hitch, 1974). WM is widely assumed to be an important contributor to essential functions in human cognition. Many higher cognitive processes rely on WM whenever they require information to be kept "online" or to be manipulated.

The concept of a memory system that is responsible for the temporary storage of information is not new. The first notion of such a memory system dates back to the 19th century. Since then, views on its nature and function have constantly evolved and changed from a relatively passive short-term memory (STM) store to a dynamic WM system (Baddeley & Hitch, 1974; James, 1980; G. Miller, Galanter, & Pribram, 1960). "In contrast to the traditional storage-orientated notion of STM, WM is considered as a more processing-orientated construct […] in which active processing and temporary storage dynamically take place" (Shah & Miyake, 1999, pp. 8). Thus, WM reflects more than temporary maintenance. It includes other processing mechanisms that help to make use of STM (Cowan, 2008). However, there is no clear-cut distinction between WM and STM (Postle, 2006; Zimmer, 2008). In fact, STM can be defined as a subcomponent within the theoretical construct of WM responsible for the storage of information. From this view, it is not much a debate about different memory systems, but rather than the use of distinct terms when looking at mechanisms underlying the maintenance of information. Since the current work is focusing on differences in nature of WM storage, no dissociation between WM and STM will be made.

A fundamental characteristic of WM is its apparent limitation in capacity. In the visual domain, WM storage capacity is usually assumed to vary between three to four objects (Cowan, 2001; Luck & Vogel, 1997; Zhang & Luck, 2008). Despite this general limit on central capacity, substantial individual differences can be observed across different subject populations. It is well-known that WM capacity declines in people with advanced age (Brockmole & Logie, 2013; Brockmole, Parra, Della Sala, & Logie, 2008) or in adults with a variety of cognitive disorders like schizophrenia (J. Lee & Park, 2005) or Parkinson's disorder (E. Y. Lee et al., 2010). Even within a healthy adult population, studies reveal reliable individual differences in estimates of WM capacity (Cowan et al., 2005; Fukuda, Awh, & Vogel, 2010; Talsma, Slagter, Nieuwenhuis, Hage, & Kok, 2005). Such individual differences in WM performance have been interpreted as important stable traits because they are strongly correlated with various measures of higher cognitive functioning (Engle, 2010; Perez & Vogel, 2011) including fluid intelligence (Cowan et al., 2005; Daneman & Carpenter, 1980; Engle, Tuholski, Laughlin, & Conway, 1999; Fukuda, Vogel, Mayr, & Awh, 2010; Heitz, Unsworth, & Engle, 2004). Consequently, it is important to better understand the nature of differences in WM and the focus of the current work is to characterize possible sources for the variation in WM capacity in healthy young adults.

1.2 The Unitary vs. Non-Unitary Nature of Working Memory

In WM literature there is an ongoing controversy about the nature of WM. Some researchers have emphasized that WM is fractionated in different components (e.g. Baddeley & Hitch, 1974) while others conceive WM as a unitary system that is independent of the nature of its content (Barrouillet, Bernardin, & Camos, 2004; Cowan, 1999; Engle et al., 1999; Oberauer, 2013). According to the first view, WM can be dissociated into two distinct memory stores, one for visual and one for verbal or auditory information (Baddeley & Hitch, 1974). Thus, interference between processing and storage are assumed to occur when involving information that affects the same domain (e.g., when they both include verbal or visual information). For instance, studies examining brain-damaged patients revealed that the functioning of verbal WM can be disrupted with intact functioning of visual WM and vice versa (De Renzi & Nichelli, 1975). Further support for the subdivision into visual and verbal WM comes from dual-task studies showing little or no interference on visual WM when the secondary task included processing of verbal material and vice versa. However, substantial impacts on the main task have been found for two tasks using only visual or verbal stimuli (Beech, 1984; Scarborough, 1972). Together, this has been taken as evidence for a functional division between verbal and visual WM processing.

Other accounts go even further and fractionate WM into finer parts. For instance, visual WM can further be subdivided into visual and spatial WM. One source of evidence for a dissociating memory for visual and spatial information is provided by dual-task techniques. These kinds of experiments have shown that a concurrent spatial task interferes with spatial memory performance and a concurrent visual task with visual memory performance. For visual memory performance, however, there was no interference from a secondary spatial task and vice versa (Tresch, Sinnamon, & Seamon, 1993; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001). Brain imaging studies with brain-damaged patients also highlight the possibility to disrupt spatial memory without influencing visual memory, or vice versa (e.g. Farah, Hammond, Levine, & Calvanio, 1988). Further evidence comes from single-unit activity recordings in monkeys, whereas neural activity during the retention interval was found in different cortical areas for spatial and visual information (e.g. Gnadt & Andersen, 1988; E. K. Miller, Li, & Desimone, 1993). Comparable results have been revealed in human neuroimaging studies of healthy adults using EEG techniques (e.g. Mecklinger & Pfeifer, 1996; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1997) or fMRI (e.g. Belger et al., 1998).

However, there is also conflicting evidence that does not support a subdivision of visual memory into visual and spatial subsystems. In particular, visual memory performance declines in conditions with task-irrelevant changes in object locations suggesting that context information is important for visual WM (Jiang, Olson, & Chun, 2000; Zimmer & Lehnert, 2006). For example, Zimmer and Lehnert (2006) have shown that WM performance for shapes declines, when the spatial configuration is disrupted. This was even the case when the names of the shapes rather than the actual shapes were tested. Therefore, it is reasonable to propose that visual and spatial information are both actively integrated into single item representations whenever this is useful to solve a given task. Changes in spatial positions would thus reduce the accessibility to the integrated item representation. Moreover, the change in spatial configuration might produce a change signal which is difficult to ignore. To conclude, spatial and visual WM might be either dissociated or integrated, resulting in different degrees of functional overlap, depending on how they are measured. Furthermore, since object identities are naturally integrated within a spatial position (Treisman & Zhang, 2006), spatial and visual information are at least to some extent linked in visual WM (see Luck, 2008 for a similiar discussion).

Although there is accumulated evidence for a subdivision of WM into different systems, there is also conflicting evidence speaking against such dissociation. For instance, D’Esposito et al. (1998) found overlaps in brain areas activated by verbal and visuo-spatial memory. It has further been shown that a task that is assumed to assess auditory WM also activates brain areas associated with perception and language, areas which should tap into visual and verbal WM (Gabrieli, Poldrack, & Desmond, 1998). Behavioral studies further demonstrate that verbal memory is disrupted by visuo-spatial processing and vice versa (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Phillips & Christie, 1977). Further evidence that supports a unitary memory view is that different memory tasks tapping into verbal or visual processes are highly correlated (e.g. Unsworth, Redick, Heitz, Broadway, & Engle, 2009). Such results cannot be explained from a WM subsystem point of view that is why this conclusion remains controversial in WM literature. Several researchers oppose the view of different WM systems and focus on the unitary nature of a single WM system (Barrouillet et al., 2004; Cowan, 1999; Engle et al., 1999; Oberauer, 2013). Instead, they emphasize a more functional role of

WM, independent of the nature of its content. They define WM as a continuous process based on the general availability of resources together with a mechanism of resource sharing. From this view, processing and storage would compete for domain-general limited resources resulting in interference whenever processing and storage has to be performed simultaneously (Barrouillet et al., 2007). A common conceptualization of the unitary memory view characterizes WM as the selected part of representations that are currently under the focus of attention (e.g., Cowan, 1999).

Taken together, a variety of WM theories proposed earlier reflect distinct characteristics on the nature and function of WM. In the current work we ourselves take the view that WM is best characterized from a functional point of view, and the question whether WM is based on a single mental resource or multiple subsystems is only tangential to the topic of the current work. Thus, although the current work focuses on WM tasks in the visual domain, we assume that our results are reflective of WM functioning overall.

2 Assessing Working Memory Functioning

2.1 Variety of Working Memory Tasks

Over the last 30 years various indicators have been developed to measure WM capacity. These tasks differ in their cognitive demands on the WM system and therefore provide different perspectives on the cognitive processes of WM functioning. Probably, the best known and most frequently used tasks for measuring WM can be divided into three different classes: span tasks, continuous performance tasks and visual array tasks which are described in the following.

Span tasks are one classic measure of WM capacity and can be further subdivided into simple and complex span tasks. Typically, simple span tasks measure the passive storage function of WM. In these tasks, participants are required to temporarily maintain a series of sequentially presented elements. Afterwards, the stimuli have to be recalled in the correct displayed order. For example, in the visuo-spatial version of this task named the “Corsi block-tapping task”, participants have to reproduce spatial locations. By contrast, complex span tasks (Daneman & Carpenter, 1980) reflect the idea that WM functioning combines passive storage as well as active processing. They are created by adding a demanding secondary processing task to a simple span task after each to-be-remembered stimulus. This secondary task thus competes for resources with passive information storage. For the most popular variations known as operation span and symmetry span (a visuo-spatial variant) the secondary task is the solving of a mathematical equation or the judgement whether a picture is symmetrical or not.

The *n*-back task is a continuous performance task (Kirchner, 1958). Participants are presented with a sequence of stimuli and instructed to continuously monitor and update the to-be-remembered information. Their task is to judge whether the currently displayed stimulus matches the item presented *n* trials before. With increasing *n*, task difficulty increases, because more items have to be kept active in order to make the correct comparison. Therefore, the *n*-back task is assumed to measure active WM functioning. The displayed information has to be kept active and needs to be updated continuously.

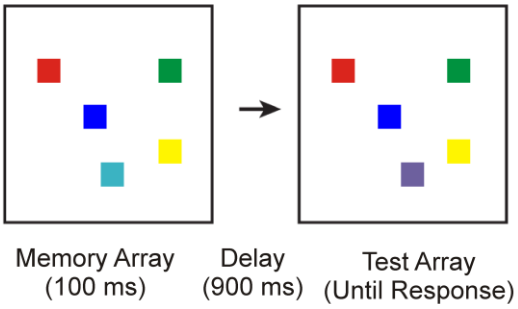

Figure 2.1. *Example of a change detection paradigm adapted from Luck and Vogel, (2013). Displayed is a change trial.*

Visual array tasks present multiple pieces of visuo-spatial information in parallel. They are typically assessed to measure the passive maintenance component of WM. A conventional version is the *change detection task*, which has been introduced by Phillips (1974) and promoted by Luck and Vogel (1997). A typical change detection task procedure is depicted in Figure 2.1. In this paradigm participants briefly study a set of objects on a *memory array*. After a brief *retention interval or delay period,* usually around one second, a *test array* appears and memory is tested. In 50% of the trials one object has changed relative to the memory array and on the remaining trials the test array is identical. Participants have to judge whether a change has occurred or not. In the present work, we will focus on WM capacity as it is reflected in change detection tasks. Advantages of the change detection task a measurement of WM functioning will be discussed in the following.

2.2 Advantages of Using a Change Detection Task as Measurement of Working Memory Functioning

The change detection task is commonly seen as a process-pure reflection of passive storage and much of the evidence for storage-based functioning of WM has been assessed with it (Awh, Barton, & Vogel, 2007; Cowan et al., 2005; Fukuda, Vogel, et al., 2010; Luck & Vogel, 1997; for a review see Luck, 2008). It is a fairly straightforward measure that involves less non-mnemonic processes during task performance than, for example, the operation span task or continuous performance task, making it a sensitive measure of WM storage only.

One major advantage of using change detection tasks is that the role of other non-mnemonic processes related to task-general processing can be easily minimized. Perceptual influences during the memory and test array can be controlled for by using simple and highly discriminable stimuli and by realizing big changes between memory and test array to facilitate the detection of a change (Awh et al., 2007; Fukuda, Vogel, et al., 2010). Secondly, influences of the response system are controlled for by using a simple “change”/”no-change” response without stressing for speed. Perhaps the biggest advantage of using a change detection task is the fact that during retrieval it is only necessary to compare the memory representations with a new set of stimuli. There is no need to manipulate or transform the retained information as there is in complex span tasks or continuous performance task. In complex span tasks, for example, the necessity to retrieve the stored items in a serial order might cause response interference, whereby reporting the first item might interfere the representations of the remaining information. As a consequence, WM capacity would be underestimated because fewer items can be reproduced than without interference. Taken together, since performance in change detection tasks is less prone to the influence of task-general processes like response interference it is an effective measurement for WM capacity (for a similar discussion see Luck, 2008).

A further advantage is the simplicity of the task. It is easy to adapt to the examination of various research questions and consequently a wide variety of approaches have been developed around this design. For example, within the framework of a change detection task, individual differences in WM capacity have been assessed by varying the number of presented stimuli (e.g. Luck & Vogel, 1997). Furthermore, one can investigate how information is represented in WM by changing the type of stimuli (e.g. Alvarez & Cavanagh, 2004; Luck & Vogel, 1997), the quality of item representations can be measured by manipulating the magnitude of change (Awh et al., 2007; Zhang & Luck, 2008), the time course of consolidation processes in WM can be estimated by displaying pattern masks shortly after the memory array (e.g. Vogel, Woodman, & Luck, 2006), presenting relevant objects together with distractors allows to measure modulations of selective attention on WM (e.g. Vogel, McCollough, & Machizawa, 2005), etc. Since the current work aimed to examine selective attention effects on WM and estimate individual differences in WM capacity, the change detection task was an advantageous measurement for WM storage.

One major issue in visual WM research is the question whether subjects store objects as visual objects or verbal labels. It is possible that participants form mental lists of verbal labels for the presented stimuli. From this perspective, performance in change detection tasks might not reflect purely visual storage processes but entail contributions of verbal WM. As introduced in Chapter 1.2 the nature of WM is still controversial and some researchers emphasize the importance of controlling for influences of verbal and visual WM. Luck and Vogel (1997), however, showed that verbal WM does not impact performance in a visual change detection task. In half of the trials verbal load conditions were added before the presentation of the memory array. Participants were required to hold and say digits presented at the beginning of the trial until the end of a trial. They compared performance on such trials with trials without verbal load and found no significant difference in performance. This has been taken as evidence that performance in change detection task is not influenced by verbal WM and reflects process-pure estimates of visual WM.

2.3 Estimating Storage Capacity of Visual Working Memory

Visual WM is generally considered to have small storage capacity. In order to quantify its upper capacity limit, researchers typically varied the number of presented stimuli within an array – *set sizes* (e.g., Luck & Vogel, 1997).

The logic of varying the number of stimuli is that participants would perform perfectly whenever their memory capacity of K items would be less than or equal to the number of presented items (*N)*. When $N > K$, the likelihood that the item displayed in the test array is actually one of those represented in WM, and hence, that the participants are able to make an accurate decision, is simply K/N. On the remaining $(1-K)/N$ trials, where the target stimulus is not stored due to the capacity limitation, a person would not know whether a change occurred or not and guess. Thus, performance should decrease continuously as N exceeds K. For example, if a participant's actual capacity is two items and the presented set size is four, the probability that a change is detected is 0.5. This probability would further decline with increasing set size. If the number of items which are required to be maintained is six, the detection probability for the same participant would be 0.3 only.

This general logic was taken into account when Pashler (1988) formulated an equation for estimating a person's visual WM capacity. Importantly, he corrected for guessing by incorporating hit rates (H) and false alarms (F) in the equation. This index of WM capacity was further improved by Cowan (2001), and the resulting formula is the following: $K=N(H-F)$, whereas K represents the assessed WM capacity. In the present work hit rates refer to proportion of correct match trials whereas false alarms are the proportion of incorrect change-trials. Response misses were declared as errors.

The validity of the *K*-Score as index of WM capacity has been shown in several experiments. In these experiments, independently of stimulus type and set size, the estimated upper limitation of WM capacity was quite constantly reached at about three to four items (Fukuda & Vogel, 2009; Luck & Vogel, 1997; Vogel & Machizawa, 2004). However, it is not yet clear whether this capacity limit is due to a fixed amount of high resolution item representations or "slots" (Cowan et al., 2005; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) that can be retained in WM or due to the total amount of information, independently of the number of items (Alvarez & Cavanagh, 2004; Bays, Catalao, & Husain, 2009; Bays & Husain, 2008). Although arbitrating between these views is a fundamental question for theories on how information is stored on WM, we will not go further into detail about the nature of WM (for a deeper discussion see Luck, 2008). In the present project, we interpreted the *K*-score as number of objects stored in WM with a fixed resolution.

The Pashler-Cowan K formula, however, only accurately estimates a person's WM capacity when being applied to above-capacity set sizes. Per definition, a person's WM index can only be as high as the largest set size realized. That is, imagine a person's actual WM capacity is *K=4* items. Accuracy in a change detection task with set size one and three would be perfect, resulting in a corresponding *K*-score of *K=1* and *K=3* items, respectively. Both estimates, however, would be underestimating the actual WM capacity of *K=4* items. Therefore, in order to accurately estimate a person's actual WM capacity the realized set size in a change detection paradigm must exceed its WM capacities. Since a priori we could not know a person's capacity, subjects completed different set sizes in the present work. We computed *K* at these set sizes and took the maximum *K* across set sizes to estimate a person's WM capacity in the respective experiments. Thus, our assessed WM capacity scores can be interpreted as a true reflection of WM storage functioning. To test for effects of set size, mean accuracies for each set size corrected for guessing (*H-F*), the so called *PR-Score,* has been used.

2.4 Neurophysiological Measures of Visual Working Memory

Behavioral experiments have shown a general limit in visual WM storage. To better understand how the storage process works, visual WM can also be examined at a neural level. A variety of neurophysiological approaches have been extensively assessed in the extent to which they measure WM load and many of the recent findings are built on electrophysiological correlates of WM (see Drew, McCollough, & Vogel, 2006 for a similar discussion). Such event-related potentials (ERPs) are typically extracted time locked to the memory array and continued during the retention interval of a change detection task.

For example, Ruchkin et al. (1997) found a negative slow wave (NSW) over the temporal-occipital electrode sites that sustained over the retention period. The amplitude of the NSW increased with visual WM load (e.g. Mecklinger & Pfeifer, 1996; Ruchkin et al., 1997) highlighting the functional significance of the NSW as a neural reflection of WM storage.

However, numerous non-mnemonic processes that occur during the performance of a change detection task might limit the functional interpretation of the NSW as a simple measure of WM. These, task-general processes (effort, arousal, sustained attention, anticipation for an event requiring a response etc.) may partly be responsible for the increase in amplitude with increasing set size and add up to the NSW. For instance, after the offset of the memory array participants already anticipate the upcoming onset of the test array and prepare for a response. Indeed, a well-studied ERP component called the contingent negative variation (CNV), which is supposed to reflect such anticipation processes, shows similar characteristics in polarity and timing like the NSW (cf. McCollough, Machizawa, & Vogel, 2007), and thus, might overshadow mnemonic activity (Vogel & Machizawa, 2004). Although some alternative explanations like anticipation have been excluded (Ruchkin, Canoune, Johnson, & Ritter, 1995), disentangling the influence of generalized effort as task difficulty increases and WM load is more critical to control for.

One useful approach to separate out specific cognitive activity from more general processes is the *contralateral control method* (Gratton, 1998). This approach is based on the contralateral hemispheric organization of the visual system and the logic is that general processes should be recordable bilaterally while WM specific processes should be prominent only in the contralateral hemisphere. The method thus isolates non-specific processes by comparing the neural activity recorded from the left and right hemisphere under certain experimental conditions. In order to do so, bilateral displays of stimuli are used and only one side of the array is relevant in any given trial. This approach allows specifying the process of interest by subtracting the electrophysiological activity measured over the contralateral from the ipsilateral hemisphere. By computing the differences between ipsilateral and contralateral slow wave such non-specific processes should be subtracted out.

Recently, this approach has been used by Klaver, Talsma, Wijers, Heinze and Mulder (1999) to examine visual WM storage functioning. In their study, participants performed a bilateral change detection task. The memory array consisted of two abstract shapes, with one shape in each hemifield. A cue at the beginning of each trial indicated which abstract shape should be remembered (either left or right side). Participants were required to maintain the relevant shape for 1500 ms until a test object appeared. During the retention interval the authors observed a posterior NSW that was more pronounced in the hemisphere contralateral than ipsilateral of the to-be-to remembered shape, which was demonstrated by calculating the difference wave between activity at hemispheres ipsilateral (task general processes) and contralateral to the target (task general and memory-specific processes). Thus, this sustained component appears to be a good reflection of WM storage functioning.

3 Contralateral Delay Activity – A Pure Neural Correlate of Working Memory Storage

As reviewed in the preceding paragraph, Klaver et al. (1999) isolated a sustained component that appears to be a useful tool to examine WM maintenance. However, because they did not manipulate the number of presented stimuli, additional studies still had to demonstrate that this ERP is really a clean measure of WM.

More recently, Vogel and Machizawa (2004) have used a similar contralateral approach like Klaver et al. (1999). Specifically, they also used a bilateral memory array to exclude task-general processes which are not related to WM maintenance, but manipulated different set sizes. They presented participants briefly (e.g., 100 ms) with different colored squares within a bilateral visual array while they retained fixation centrally. Their task was to maintain only the objects in a certain hemifield, as indicated by a cue. After a short (e.g., 1000 ms) retention interval, memory was tested with the presentation of a test array that was either identical or exhibited a change in the color of one item. Similar to Klaver et al. (1999), they observed a large negative-going sustained slow wave over the posterior parietal and lateral occipital electrode sites across the retention interval. This slow wave was more pronounced in contralateral electrodes to the memorized hemifield, which was demonstrated by calculating the difference wave between the activity measured at the ipsilateral and contralateral hemisphere. According to the contralateral control approach this contralateral-specific activity should reflect the memorized information. They referred to this component as *contralateral delay activity* (CDA) which is also known as the sustained posterior contralateral negativity (Robitaille & Jolicoeur, 2006). In the present work, we will use the nomenclature CDA.

The CDA is a component with negative voltage that has been shown for stimuli that vary in different dimensions, such as color (Vogel & Machizawa, 2004), orientation (McCollough et al., 2007; Vogel, McCollough, et al., 2005) and shape (Luria & Vogel, 2011). It starts approximately 200 ms after the onset of the memory array and continues throughout the duration of the retention interval (e.g. 900 ms) (McCollough et al., 2007; Vogel & Machizawa, 2004), and therefore exceeding the time duration of iconic memory (Vogel et al., 2001).

3.1 What Does CDA Amplitude Reflect: WM Load or Other Task General Factors?

The strongest evidence that the CDA is a process-pure neural correlate of WM maintenance was the finding that CDA amplitude is sensitive to the number of memorized items. CDA activity increased for array sizes of one to three items until it reached a limit with arrays of approximately four items per side (Vogel & Machizawa, 2004). Consequently, the amplitude of the CDA seems to be exhausted at the same point as behavioral estimates of WM capacity would predict (see Chapter 2.3). Additionally, CDA activity seems to be larger for correct than for incorrect responses (McCollough et al., 2007; Vogel & Machizawa, 2004), suggesting that this neural activity is important for correct task performance. More precisely, it seems to reflect maintenance of successful representations. As mentioned before, however, several other cognitive processes are also likely to affect CDA amplitude. Thus, the increase in CDA amplitude with larger set sizes may partially be a result of other processes. We see at least three alternative explanations which have to be ruled out before the CDA can be accepted as a measure of WM load (cf. Perez & Vogel, 2011).

The Influence of Task-General Processes such as Effort or Arousal

The sustained slow potential might also reflect non-specific processes such as effort or arousal which are related generally to the task. As explained above, this is an important challenge for the validation of any neural correlate of a cognitive process and the specificity of it as reflection of truly mnemonic activity is still necessary (McCollough et al., 2007). With increasing WM load, task general processes such as effort, arousal and task difficulty do also increase. To rule out this possibility, Vogel and Machizawa (2004) also assessed memory arrays that were above the known limits of WM capacity (arrays of six, eight or ten items). Their logic was as follows: If the CDA reflects task-general processes such as task difficulty, then its amplitude should continuously become larger with larger set sizes. Alternatively, if the activity reflects WM storage, then one would expect the amplitude to reach an asymptote when a person’s WM capacity limit is reached. The results revealed that CDA activity increased until it reached an asymptote at array sizes around four items. No further increases for larger set sizes have been found. Though general processes such as task difficulty steadily increased for arrays above a person’s WM capacity limit, CDA amplitude did not. This has been taken as evidence that the task general processes cannot explain larger CDA amplitudes from set size one to four (see also McCollough et al., 2007).

Controlling for Perceptual Influences

Another alternative explanation concerns the perceptual requirements of a memory array. With increasing number of to-be-memorized items, the amount of perceptual effort also increases. In order to test for this, Ikkai, McCollough and Vogel (2010) compared CDA activity for arrays containing stimuli with high and low contrast and different set sizes. Items displayed in low contrast should require much more perceptual effort. Thus, if CDA amplitude is sensitive to perceptual requirements, the activity should be larger for arrays containing items with low relative to high contrast. Behaviorally, they found performance to be decreased in the low contrast condition. However, CDA amplitude did not reflect this. Its activity was only sensitive to the number of presented stimuli irrespective of whether the perceptual processing was effortful (low contrast) or not (high contrast), supporting the interpretation that CDA activity reflects the number of memorized representations.

The Influence of Item Location and Spatial Context

It seems plausible that CDA amplitude is sensitive to the spatial information of the objects since the number of objects is typically confounded with the number of positions to be retained. To rule out this possibility, a control experiment has been conducted were the memory array was split up into two successive memory arrays, where items from both had to be retained. Critically, in some of the trials, the item of the second memory array appeared exactly at the same position as the item displayed in the first memory array. This design allowed to directly test whether the CDA reflects the number of presented items or attended locations. In line with the first explanation, the results of the control experiment only varied with the number of items irrespective of whether the items were presented at different locations or at the same location (Ikkai et al., 2010).

Another potential confound influencing CDA amplitude is the spatial context or spatial relation between the items. In previous experiments, arrays with larger set sizes covered a larger spatial area within the hemifield compared to smaller set sizes. Consequently, with smaller, but not with larger set sizes, it is not necessary to dilate the focus of attention over a larger space. From this perspective, it may not be the increase in set size that accounts for the observed raise in CDA amplitude but the size of the required attentional spotlight. However, a study conducted by Mccollough et al. (2007) suggests that this interpretation is unlikely. Specifically, they manipulated the spatial distance between the-to-be remembered items, one spaced and one compact condition respectively, while keeping the number of items constant. No effects of spatial distance on CDA activity were found. Its amplitude was solely modulated by the number of items.

Together, the reviewed studies demonstrate that the CDA is a good indicator for the neural reflection of WM maintenance. Next, we will discuss whether differences in CDA amplitude are reflective of variations in WM capacity.

3.2 The Sensitivity of CDA Amplitude to Individual Differences in WM capacity

To further test the sensitivity of CDA amplitude to the number of items stored in WM, Vogel and Machizawa (2004) examined whether a person’s WM capacity specifically determines when his or her delay activity reaches a limit. If so, CDA amplitude for participants with low WM capacity should reach this limit faster than persons with high WM capacities, who are able to retain more items in WM. However, it is not easy to quantify the precise CDA amplitude predicted for each individual based on a categorical data set such as set size. For instance, there is no array size of 3.6. Instead, Vogel and Machizawa (2004) calculated the amplitude increase between two and four items. The logic behind this was that the increase in CDA amplitude should be dictated by a person's capacity. For instance, if a person has a low WM capacity of less than two items, its capacity resources should be completely consumed at two item as well as four item arrays, resulting in identical CDA amplitudes for two and four items. By contrast, for a person with a high WM capacity of nearly five items, his or her WM limit would not be reached at set size two. Consequently, the amplitude for set size four should show a large increase to set size two. Indeed, there was a strong positive correlation between a person's memory capacity, as estimated with the *K*-Index and the point at which the CDA reached a limit.

Taken together, CDA amplitude is apparently a pure reflection of item storage. Aside from being finely sensitive to the amount of information currently stored in WM, CDA amplitude is also sensitive to individual differences in WM capacity. Since the main focus of this dissertation project is disentangling causes underlying individual differences in WM capacity, we will employ CDA amplitude as electrophysiological reflection of item storage in Experiments 3 and 4 (Chapters 8 and 9). In the following we will provide a deeper insight in possible causes related to individual differences in WM storage.

Part 2

The Nature of Individual Differences in Working Memory Capacity

4 Variability in Storage Space or Efficiency of Attentional Control?

Aside from the robust average WM capacity of three to four items, several studies observed substantial individual differences in storage space. Across a healthy population, estimates of WM capacity ranged from 1.5 to 5 items (Awh et al., 2007; Fukuda, Awh, et al., 2010). Several potential causes for this are discussed.

In the preceding chapters, we defined WM as a system responsible for the temporary maintenance of information (see Chapter 1). This view implies that the primary factor limiting WM capacity is the amount of storage space or more precisely the number of discrete representations or “slots” a person is able to retain (Awh et al., 2007; Luck & Vogel, 1997; Zhang & Luck, 2008). At each slot a single individuated item or chunk of information can be stored. Thus, the more slots a person has, the more information he or she is able to retain (see also Chapter 2.3). However, an alternative viewpoint argues that individual differences in WM capacity are due to variations in the ability to control the gating of relevant information into WM including the ability to resist distraction. The actual amount of information people are able to store might be relatively fixed across individuals at approximately four slots. What individuals differ in is how well each person can control what is stored in these slots. According to this idea, variance in WM capacity is partially caused by individual differences in cognitive control process or attention control (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). The account makes the simple prediction that tight associations between attention control and WM will lead to a significant relation between the ability to select relevant items for encoding and WM capacity (Awh, Vogel, & Oh, 2006). This viewpoint is supported by multiple studies suggesting a tight link between memory capacity and control of attention. Importantly, many of these studies utilized attentional tasks with minimal memory requirements but high needs of attention control capabilities, specifically in the face of competition between habitual response schemas and the actual required task demands (Conway, Cowan, & Bunting, 2001; Heitz & Engle, 2007; Hutchison, 2011; Kane et al., 2001; Kane & Engle, 2003; Machizawa & Driver, 2011; Redick & Engle, 2006). Across all these tasks used in the different studies, WM capacity correlated with performance on the attentional task. For instance, high WM capacity individuals perform better on Stroop tasks (in which one must report the ink a color word is written in while ignoring the meaning of the word, e.g. Hutchison, 2011; Kane & Engle, 2003) and the antisaccade tasks (wherein people are required to look away from a target, e.g. Unsworth, Schrock, & Engle, 2004). These findings strongly suggest that the ability to control attention is associated with WM capacity.

4.1 Attentional Selection and Working Memory Storage

From the beginning of present WM research, most theories agreed on the need for regulation and control of information (e.g., Atkinson & Shiffrin, 1968). However, the issue of control processes was only limited to those processes involved in pure memorization such as rehearsal (cf. Shah & Miyake, 1999). Given that WM has a very limited online capacity, it is of considerable importance not to let irrelevant information consume space in first place. Thus, the ability to process or select relevant information at the expense of irrelevant information before it enters WM is crucial for optimal use of WM storage space.

Many researchers have already proposed a common link between selective attention – the ability to center our attention on relevant elements while other things are completely blended out – and WM (for reviews see Awh et al., 2006; Fougnie, 2008). They make the simple claim that the better people are at controlling the access of information into WM, the more efficiently the storage space is used. If individuals are perfectly efficient in focusing on items that are currently necessary to complete a certain task, WM capacity is only filled with relevant information. By contrast, irrelevant information might also be represented if persons have poor selection mechanisms. “In this sense, attention can serve as a kind of “gatekeeper” for WM, by biasing the encoding of information toward the items that are most relevant to the current processing goals” (Awh et al., 2006, p. 202). Next, we review how attentional selection mechanisms contribute to individual differences in WM capacity.

4.2 Investigating Individual Differences in Selection Mechanisms and Working Memory Capacity

A sequence of studies has revealed that individuals with high and low WM capacity differ in their ability to control what information will be maintained in WM (Fukuda & Vogel, 2009; Jost, Bryck, Vogel, & Mayr, 2011; Liesefeld, Liesefeld, & Zimmer, 2014; McNab & Klingberg, 2008; Vogel, McCollough, et al., 2005). In such studies, participants take part in a change detection task as described in Chapter 2.1. Critically, on some of the trials both relevant and irrelevant stimuli are presented simultaneously engaging attention control processes and participants are instructed to remember only the relevant ones. For example, participants may perform feature-based selection such that they have to select items based on a certain color (Vogel, McCollough, et al., 2005). For the upcoming memory comparison, only relevant information is tested. One can directly estimate the effect of selection processes on WM storage by comparing trials with and without distractors in accuracy and/or CDA amplitude as electrophysiological reflection of WM maintenance. For example, if participants are perfectly efficient in controlling the storage of information into WM, CDA amplitude in distractor-present trials (e.g., two targets and two distractors) should be identical to *pure-target trials* with the corresponding number of targets (two). By contrast, if the selection mechanism of an individual is poor and all items are unnecessarily stored in WM, CDA amplitude in the distractor-present trials should be identical to the condition when the same number of stimuli is presented, but all are targets (set size four).

In one particular study conducted by Vogel and colleagues (2005) participants were required to remember the orientation of colored rectangles (e.g. red) while they recorded Electroencephalography (EEG). Crucially, they added distractor-present trials wherein participants were required to select only a subset of items for WM storage. In these trials, participants should remember two red items out of an array consisting of two red and two blue items. On the remaining trials, arrays consisted of either two or four items per side (pure target trials). As an electrophysiological index for WM maintenance, CDA amplitude was used. They divided all subjects into two groups, high and low WM capacity individuals respectively, based on their behavioral estimated WM capacity (*K*-Score). In individuals with high WM capacity CDA amplitude of remembering two items was the same as in the condition where two targets were presented among two distractors, suggesting that these individuals were efficient in selecting only relevant items for WM storage and excluding irrelevant ones. By contrast, for participants with low WM CDA amplitude for distractor-present trials was identical to those trials of memorizing four relevant stimuli, indicating that low WM capacity individuals were inefficient at controlling the access of items into WM storage. Each subject's filtering efficiency extracted from CDA amplitude strongly correlated with the estimated behavioral WM score (see Vogel, McCollough, et al., 2005 for details quantifying the efficiency index).

However, previous research showed that color-based selection is very difficult and tends to be inefficient relative to selection of other attributes (Shih & Sperling, 1996). Consequently, it is likely that the relationship between WM capacity and selection mechanisms is only present under demanding conditions. To rule out this possibility, Vogel and colleagues (Fukuda & Vogel, 2009; Vogel, McCollough, et al., 2005) conducted a series of control experiments. Instead of color-based selection they modulated selection based on location (Vogel, McCollough, et al., 2005) or shape (Fukuda & Vogel, 2009). For location-based selection, items were presented in the upper or lower quadrant and subjects were cued to remember the stimuli of only one of the quadrants (targets). In another version of a bilateral change detection task, colored squares were used as targets and rectangles as distractors. In both studies, CDA amplitude was a valid measure for the number of items being maintained in WM. It varied as a function of WM capacity and efficiency of target selection. More precisely, CDA activity in the distractor-present condition for high WM capacity individuals was the same as in the pure-target condition with the corresponding number of targets. By contrast, for low WM capacity individuals the CDA in the distractor-present condition and pure-target trials with the same number of stimuli but all being targets was identical. This has been taken as evidence that CDA amplitude patterns observed in Vogel's et al. (2005)

experiment are not restricted to challenging selection conditions. The ability to regulate which items enter to working memory seems to be crucial.

4.3 Selective Attention Modulates Efficient Selection in Working Memory

In the preceding section, we reviewed evidence that participants who are able to remember more items over short periods of time are also more efficient in controlling what information is maintained. Thus, one main component in understanding individual differences in WM capacity is to better understand how selection mechanisms contribute to individual differences in WM capacity. In line with theories of visual attention we propose a gating system or attentional filter that seems to enhance relevant and suppress irrelevant information. Thus, relevant and irrelevant information compete for limited processing resources. The competition is biased, however, towards information that is currently attended. Unattended information does not make demands on processing capacity (Bundesen, Habekost, & Kyllingsbaek, 2005; Bundesen, 1990; Desimone & Duncan, 1995; Duncan, 1981; Olivers & Meeter, 2008). Thus, one cause of individual differences in selective attention might be the ability to focus attention on relevant items and to inhibit irrelevant items

In a series of studies, Fukuda and Vogel (2009) investigated whether WM capacity is associated with an individual’s susceptibility to attentional capture by distractors. In one particular experiment, subjects completed a bilateral change detection task with distractor-present trials. Shortly after the offset of the memory array, task-irrelevant dots were flashed either at the target or the distractor locations. The logic behind this procedure was that electrophysiological markers should show enhanced evoked responses at locations to which attention was allocated. If people primarily focus their attention on targets, then the electrophysiological response evoked from dots at target locations should be increased relative to the response from dots at distractor locations. As electrophysiological index for attentional selection the P1/N1 complex was used, components which are assumed to be sensitive to spatial attention (Luck & Hillyard, 1994). The higher the amplitudes of the P1/N1 complex, the more attention is assumed to be allocated to a certain position. Attentional capture was defined as the amplitude difference between the P1/N1 responses to dots flashed at locations of targets and distractors. WM maintenance and attentional filtering, by contrast, was assumed to be reflected by CDA activity. First, they replicated the relationship between unnecessary storage of irrelevant information and CDA amplitude. Furthermore, and more importantly, the results revealed strong positive correlations between attentional capture and WM capacity. That is, individuals with high WM capacity showed larger P1/N1 responses to dots at target locations than individuals with low WM capacity, indicating that high WM capacity individuals were less prone to allocate attention on distractors. Importantly, the attentional capture effect was also related to the CDA unnecessary storage effect as described before. Individuals who were less able to control the focus of attention on targets also maintained more irrelevant items in the later retention period. Thus, selective attention mechanisms are tightly associated with individual differences in WM capacity as well as the efficiency of using WM resources. The aim of our first experiment was to further characterize the relationship between the engagement of selective attention on targets and WM capacity and is described in the following.

5 Experiment 1: Working Memory Capacity and Voluntary Selection Mechanisms

5.1 Introduction

Much research suggests that attentional mechanisms play a critical role in efficient WM functioning. Their primary purpose seems to be the selection of relevant and the inhibition of irrelevant information (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Fukuda & Vogel, 2009; Kane et al., 2001; McNab & Klingberg, 2008; Vogel, McCollough, et al., 2005). Thus, knowing more about attentional control and its contributing selection mechanisms is crucial for understanding differences in WM capacity.

In the preceding chapters, we have reviewed evidence that the focus of attention influences the probability of storing information in WM, such as that information which is currently attended is biased for encoding relative to unattended information (Desimone & Duncan, 1995). We further argued that individuals which are less efficient to control the engagement of attention on task-relevant information, probably are also less efficient at excluding irrelevant information from being stored in WM (for a review see Awh & Vogel, 2008). Thus, the ability to orient attention on relevant information seems to be crucial for optimal WM functioning and individuals with high and low WM capacity differ in their efficiency of doing so (Fukuda & Vogel, 2009; Heitz & Engle, 2007). However, memory processing is not only influenced by the allocation of attention to a particular item but also the time attention dwells on the to-be-stored information (Hollingworth, Williams, & Henderson, 2001; Williams, Henderson, & Zacks, 2005). Once objects are within the focus of attention, they gain advantages in information processing (Eriksen & James, 1986) while fewer processing resources are allocated outside the focus of attention (Handy, Soltani, & Mangun, 2001; Lavie, 1995). Thus, the less time attention dwells on a presented item, the lower is the probability that this item will be encoded into WM. In a study that tested this idea, Fukuda and Vogel (2011; see also Cashdollar et al., 2013) evaluated whether WM capacity is associated with the speed of disengaging attention from the information that captured the attention in the first place. In their study, participants completed a visual search task. In some of the trials an irrelevant peripheral flanker appeared prior to the search display. The flanker was either presented in the target color or not and its onset was assumed to capture attention. Critically, they varied the stimulus onset asynchronies (SOAs) between the flanker display and the presentation of the search array. Interestingly, at the shortest SOA (50 ms) flanker impacted search performance for high and low WM capacity individuals. However, performance costs at the 150 ms SOA varied substantially across both WM groups, with no decrease in costs for low WM capacity individuals, indicating that they needed more time to disengage their focus of attention once it has been captured. Therefore, the individual's speed of disengagement may be a critical trait which determines WM capacity. If low WM capacity individuals need more time to do so, distractors might be processed and unnecessarily represented in WM competing with relevant items for storage space.

However, the slower disengagement was specific to flankers that shared the target defining selection feature, namely the same color. Those flankers that were presented in different colors did not slow down attentional disengagement. Thus, individual differences in WM capacity were only associated with delayed disengagement upon target feature contingent capture. According to the contingent capture account (e.g. Folk, Remington, & Johnston, 1992; Folk & Remington, 2006), allocation of attention depends critically on selection features, that is, the attributes for which attention is set. If a stimulus contains the relevant attribute, it will be selected for processing. The initiation of a target response will be triggered. Only if the processed stimulus has been identified as distractor, its further processing will be stopped. According to this view, disengagement operates at a late stage of processing after the object has been selected for encoding and after it has been classified as distractor. Yet, attention can influence encoding in multiple stages of processing. This includes both post perceptual processes (Deutsch & Deutsch, 1963) and early sensory processes (Broadbent, 1958). In fact, there is also support for an association between early visual processing prior to (Murray, Nobre, & Stokes, 2011) or at the moment of selection (Vogel, Luck, & Shapiro, 1998; Zanto & Gazzaley, 2009) and we ourselves believe that such early selection processes play an important role in explaining why individuals with low WM capacity are less efficient in controlling which information enters WM.

In studies showing unnecessary storage costs in CDA pattern (Jost et al., 2011; Liesefeld et al., 2014; McNab & Klingberg, 2008; Vogel, McCollough, et al., 2005), distractors never contained the target defining feature. Thus, according to the contingent capture account they could in principle be excluded from further processing via selection mechanisms. For example, participants being prepared that distractors may appear could perhaps boost processing of task relevant items so that distractors never win the race for representation. By doing so, they shield WM against distraction. Slow disengagement would be unimportant in this case because distractors would never be erroneously selected as targets. Recently, Rutman, Clapp, Chadick and Gazzaley (2010) explored the temporal dynamics of electrophysiological activity associated with selective encoding and its influences on subsequent WM performance. In their study participants took part in a selective-delayed recognition paradigm. More precisely, participants saw overlapped images of natural scenes and faces and were instructed to remember only scenes or faces and to ignore the irrelevant image. Their results revealed that goal-orientated processing (the selection of relevant and suppression of irrelevant information) begins as early as 97 ms after stimulus presentation (P100 component). Furthermore, and more importantly, the extent to which participants were able to selectively focus on task-relevant information was correlated with each participant's WM performance. This finding highlights the influence of early sensory modulation on subsequent memory performance.

We reason that individual variations in WM capacity might be reflective of variations at early sensory processing steps. The aim of Experiment 1 was to investigate the possibility that individual differences in WM capacity are reflective of variations in the engagement of attention. We estimated individual differences in WM capacity based on WM performance in a classical color change detection task as described in Chapter 2. Furthermore, we implemented two attention tasks to evaluate the relationship between attention control and WM capacity.

To measure individual differences in the ability to voluntarily control the focus of attention on targets we used a modified variant of the antisaccade task. The antisaccade task is an attentional task with minimal memory requirements, nevertheless performance correlates with WM capacity (Kane et al., 2001; Unsworth et al., 2004). Moreover, the role of saccade execution has recently been linked to attention control (Edlin & Lyle, 2013). In our variant of the task – called cued categorization task – the task demands should be comparable to those in an antisaccade task but do not require the measurement of eye movements. Participants had to identify the color of a target item, which was defined by its location. We realized three different versions of the task. In two of them cue-dependent allocation of attention was necessary with different amounts of executive attention control. In these trials, a cue indicated 100 % validly the target's location and participants were instructed to use the information of the cue to voluntarily allocate attention towards the target location. In order to make cue processing and use of its information necessary, the probe displayed a competitor at another location than the target location. Thus, the presence of the competitor was a crucial manipulation to test WM capacity related effects in the control of attentional allocation. However, in contrast to studies testing the effects of attentional disengagement, the competitor never shared the selection feature of the target since the target was in advance defined by its position.

The cue either informed participants that the target would appear at the cued (same) location (stay trials) or at the opposite side of the cued location (shift trials). When the target appeared at the same location as the cue, attention allocation is thought to be automatically triggered and no higher attention control mechanism should be involved (like on prosaccade trials). Conversely, when the target will appear at the opposite side, a voluntary initiation of an attention shift must be programmed to the new target location. Like on antisaccade trials, attention control processes should operate. In sum, our task realized two different conditions of directing attention to targets. In stay trials, nothing had to be done additionally and the incoming target at the actual attended location had to be processed. In shift trials, an additional voluntary attention shift was necessary which made attention control necessary. If the implementation of this shift is too slow or too error prone the competitor will be selected as the target and its color will be classified. Because we assumed that low WM participants are less efficient in the voluntary engagement of attention we expected better performance for high WM than low WM participants in shift trials. In stay trials, we expected no or only small differences because it was not necessary to change attentional focus. For the purpose of comparison we realized a third condition in which only one target item was presented. Because in the baseline condition the target is a single stimulus that is displayed it should be automatically selected and we therefore expected similar performance between the two groups.

Additionally, we hypothesized that participants with high or low WM capacity differ in the speed of their control processes. In order to test this, we realized two different cue to target SOAs. The time courses of the SOAs were chosen to guarantee optimal utility of the cue. Wright and Ward (1994) reported that the effectiveness of information cues reaches a maximum level at SOA of 300 ms and remains stable across further increases in SOA. Hence, the shortest SOA we realized in our study was set to 300 ms and we contrasted this with a longer SOA of 450 ms. Thus, the realized SOAs between cue and target presentation were long enough to evaluate the symbolic content of the cue, and any time dependent costs should therefore reflect individual differences in the ability to orient attention. Specifically, we expected high WM but not low WM participants to be able to shift attention even within the short SOA, so that SOA should influence performance only for low WM participants.

To specify the exact relationship between WM capacity and attention control, participants further completed the attentional network test (ANT) – a low-level attention task assessing different functions of attention (Fan, McCandliss, Sommer, Raz, & Posner, 2002). One view of attention is that it consists of different, interrelated functions. Besides the already introduced ability to orient attention on relevant information in face of competing sensory information for privileged processing, two further functions are distinguished, alerting and executive control respectively. Alerting is proposed to reflect the general ability to prepare and sustain responsiveness to sensory signals and executive control is assumed to resolve conflicts in information processing among competing mental processes (Fan et al., 2002; Petersen & Posner, 2012; Posner & Petersen, 1989). The main function of implementing the ANT was to explore whether differences in WM capacity corresponds to differences in varies functions of attention or if they are specific to orienting.

5.2 Methods

Participants completed a battery of cognitive tasks including different attention and memory tasks. The task order was differently across participants. For the purpose of this dissertation project performance in the color change detection task, the cued categorization task and the ANT are of central importance and will be described in the following.

5.2.1 Participants

Sixty-seven volunteers were recruited for participation in exchange for 8€ per hour or course credit. Three participants were excluded because their performance on the cued categorization task was below chance level, three participants due to experimental errors and one participant showed a PR-score below chance level for array size four in the change detection task. All analyses were based on the remaining sixty participants (age range = 15-35 years, $M = 23.73$, 41 female). This and all subsequent experiments have been conducted in accordance with ethical guidelines and received ethical clearance. Participants gave informed written consent after the nature of the study has been explained to them.

5.2.2 Stimuli

Change Detection Task

Memory arrays were presented within a 9.8° × 7.3° region on the monitor against a grey background. Stimulus positions were randomized with the restriction that all stimuli were separated by at least 2° center to center. Stimuli were randomly chosen from a set of seven colored squares (blue, green, red, yellow, white, black and purple) with a size of 0.65° × 0.65°.

Cued Categorization Task

All stimuli were presented against a grey background. Cue items subtended a visual angle of 0.3° and provided valid information of the target’s location. This was achieved via the position of the cue. In stay trials, the stimulus appearing at the same position was target and in shift trials the stimulus at the horizontal side of the display. Circles indicated stay trials, whereas diamonds indicated shift trials. For baseline trials, a blank display was presented for the same duration as the cue. The mask array contained of two different squares filled with random lines. They subtended a visual angle of 1.16° × 1.16°. The masks were replaced by two colored squares (0.7° × 0.7°) as probe items. Square colors were randomly chosen from a set of four highly discriminable colors (red, blue, green or yellow) with the restriction that no color could appear twice within the same array. For baseline trials, only one target appeared. Target, cue and competitor were shown at locations 11.5° of visual angle to the left and right of the center.

Attentional Network Task

Stimuli consisted of a row of five horizontal lines, with arrowheads pointing either left or right. The arrowhead in the center was the target. It was either flanked by arrowheads pointing into the same direction (congruent condition) or different direction (incongruent condition), or by horizontal lines (neutral condition). Stimuli consisted of 0.55° of visual angle and each stimulus was separated by 0.06° of visual angle. In total the stimuli obtained a visual angle of 3.08°. To implement an attentional orienting component target and flanker stimuli were presented either 1.06° above or below fixation cross in the center of the screen.

Cue stimuli were asterisks. In total four different types of cues were used: no cue, center cue, double cue or spatial cue. For the no cue condition, participants just saw a fixation cross. For the center cue condition, the cue was presented at the center of the screen at the location of the fixation cross. For the double cue trials, two cues appeared at the possible target positions – one below and one above the fixation cross. Spatial cues appeared either above or below the fixation cross and indicated 100% validly the target position.

5.2.3 Procedure

Change Detection Task

To measure an individual’s working memory capacity, we used a centralized color change detection task as described in Chapter 2. Subjects viewed (for 100 ms) four or six colored squares on a gray background. After a brief blank delay period of 900 ms, memory was tested with the presentation of a test array. The test display remained on the screen for maximally 2000 ms or until the participant made a response, whichever came first. Participants had to detect a color change that occurred in 50% of the trials. In change trials, only one square changed to a different color in the color set with the restriction that no color could appear twice at the present display. The location of the stimuli always remained the same (see Figure 5.1). Subjects pressed one button to indicate if the array was identical and another to state a difference. Forty trials were presented for each set size. Prior to this, participants completed ten practice trials with feedback indicating a correct or false response.

We computed K_{max} as described in chapter 2.3.

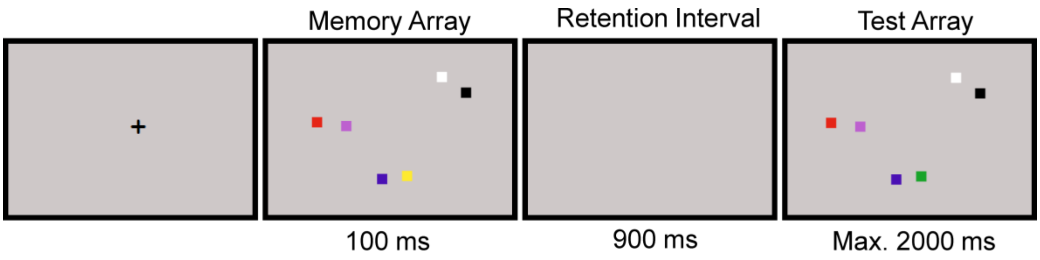

Figure 5.1. *Design of the color change detection task of Experiment 1. Depicted is a change trial.*

Cued Categorization Task

The procedure is illustrated in Figure 5.2. Participants were required to categorize the color of a target item. On two-thirds of the trials the target was accompanied by a color competitor: an identical square of a different color on the opposite side. At the beginning of each trial, the word “ready?” was presented for 1500 ms to warn participants that a trial was about to start. A black fixation cross (green in baseline trials) appeared for a time period which was randomly chosen from 500-1500 ms. In the cued condition, a peripheral cue was flashing for 250 ms. The cue provided valid information of the target's location. On stay trials, the item appearing at the same location as the cue was the target. By contrast, on shift trials the stimulus appearing at the opposite side was the target. On the remaining trials, a blank display was presented for the same duration as the cue and an isolated item was shown as the target either on the left or on the right. After the offset of the cue display, at both locations a square was presented as a mask for 50 or 200 ms. Masks were replaced by two colored squares as probe items. The response was delivered by pressing the button on the response pad that matched the color of the target. At the end of the 1700 ms interval or after the participant made a response, the display turned blank for 1700 ms. Participants completed 180 trials in total, sixty trials for every cue type. All trials were randomly mixed. Before the test procedure started, participants performed a practice block consisting of twelve trials with feedback about the correctness of the measured response.

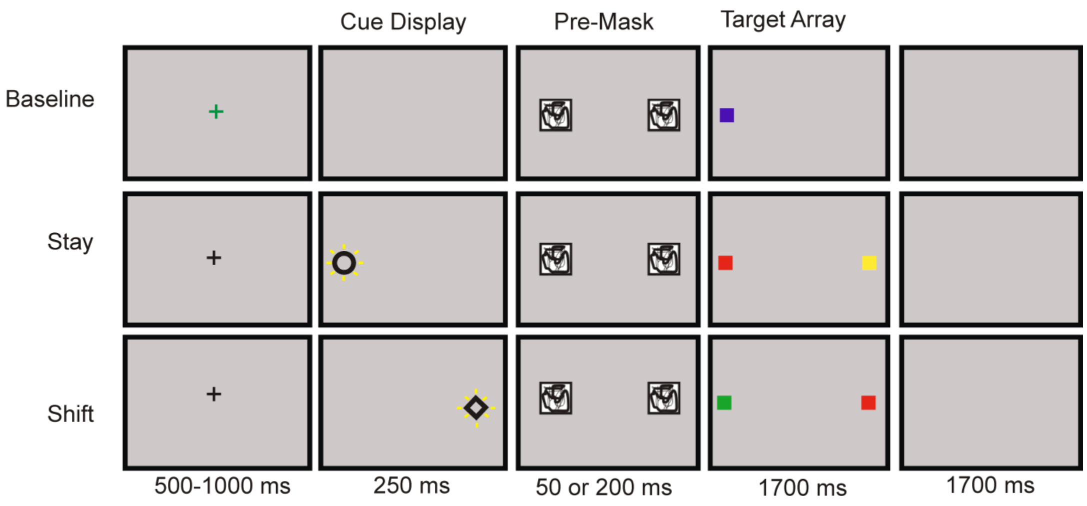

Figure 5.2. *Schematics of the experimental procedure of the cued categorization task in Experiment 1. The cue was presented at the peripheral display location and flashing for 250 ms. The target array contained one or two colored squares which remained for 1700ms on the screen or until response. On cued trials, the target location was defined by the cue.*

To check whether cues could be identified, all participants took part in a short block wherein they needed to classify the cue's shape at the beginning of the experiment. In this block, participants completed a minimum of ten trials and continued until reaching a performance of at least 80% correct or a maximum of twenty trials.

Attentional Network Task

The materials and procedure for the ANT followed from the information that has been previously published (Fan et al., 2002). The experimental procedure is depicted in Figure 5.3. At the beginning of each trial, a fixation cross appeared for a variable time of 400 to 600 ms. Then, one of the four cue types was presented for 100 ms. The implementation of multiple cues is crucial and allowed to specify the alerting and orienting component. Alertness in the ANT is involved in all trials containing a cue informing participants on the upcoming flanker display. Orienting is involved by reallocating attention from the fixation cross to the target stimulus in the center of the screen. After the offset of the warning cue, participants saw a fixation cross for a further 400 ms and then the target display appeared. Both target and flankers were displayed together. Participants were instructed to classify as quickly and accurately as possible the direction the target was pointing to. After 1700 ms or the participant's response, whichever came first, there was a further fixation period. The duration of the inter-trial-interval was calculated as 3500 ms minus the duration of the first fixation cross minus reaction time.

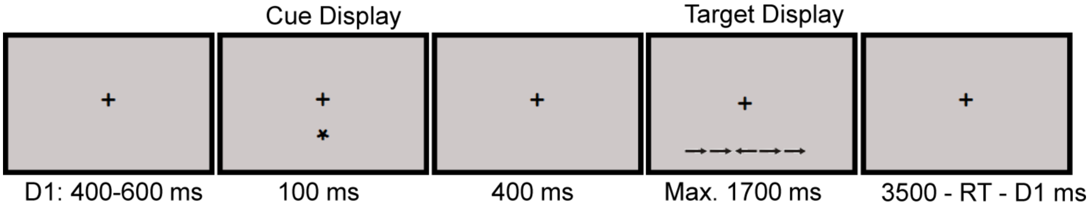

Figure 5.3. *Example of the procedure of the ANT assessed in Experiment 1. Depicted is a trial with incongruent flanker and spatial cue.*

The ANT consisted of 24 trials with feedback about correctness. Then the experimental procedure began. Participants underwent three experimental blocks with no feedback. Each block consisted of 96 trials (4 cue condition× 2 target location × 2 target direction × 3 flanker condition × 2 repetition). All trials were randomly mixed.

5.3 Results

5.3.1 Working Memory Task

The mean WM capacity estimate was 3.74 (*SD* = 1.00) ranging from 1.40 to 5.70. Participants were divided into two groups by a median split, high capacity (*M* = 4.56, *SD* = 0.54) and low capacity (*M* = 2.92, *SD* = 0.60) individuals respectively.

5.3.2 Cued Categorization Task

Figure 5.4 shows the mean accuracy achieved by high and low WM capacity individuals in all experimental conditions. On baseline trials, all participants performed equally irrespective of WM capacity or SOA. However, the cue conditions in which a competitor was presented together with the target seemed to make the task harder for low WM capacity individuals. This is most pronounced on shift trials and a short SOA. No such effects were found for high WM capacity individuals.

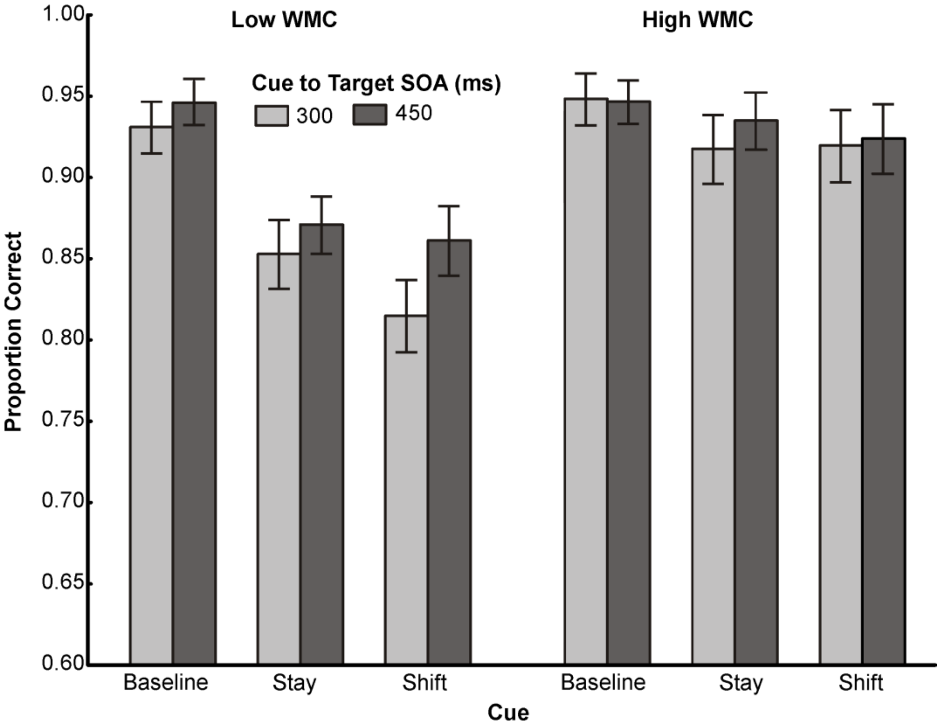

Figure 5.4. *Accuracy data as a function of cue and SOA for both WM capacity groups in Experiment 1; error bars represent plus or minus one standard error of the mean.*

A three way 3 (Cue: baseline, stay, shift) × 2 (SOA: 300 vs. 450) × 2 (WM Capacity: high vs. low) repeated measure analysis of variance (ANOVA) with WM capacity as between subject factor was conducted to examine the effect of cue and SOA on accuracy for the two capacity groups. We do not report main effects because they are qualified by two significant two way interactions, Cue × WM capacity and SOA × WM capacity respectively. The two-way interaction of Cue and WM Capacity, $F(2, 116) = 3.83$, $p < .05$, $\eta_p^2 = .06$, suggests a differential relationship of accuracy for cues between high and low WM participants. No differences in accuracy between cue conditions were found for high WM individuals (largest $F(1, 58) = 1.44$, $p = .24$). In contrast, for low WM participants, accuracy in shift trials were lower compared to baseline, $F(1, 58) = 21.93$, $p < .01$; even performance on stay trials was significantly reduced relative to baseline, $F(1, 58) = 13.88$, $p < .01$. The difference between stay and shift trials was not significant, $F(1, 58) = 1.93$, $p > .05$). Direct group comparisons between low and high WM capacity individuals revealed that accuracy in shift trials was significantly greater for high WM individuals, $F(1, 58) = 8.78$, $p < .01$. As expected, no differences in baseline were found ($F < 1.00$).

Table 5.1. *Mean accuracy and standard deviations of participants with high and low WMC in each condition of the ANT as assessed in Experiment 1.*

	Cue			
Flanker	No	Center	Double	Spatial
High WMC				
Neutral	.99 (.005)	.98 (.006)	.99 (.005)	.99 (.005)
Congruent	.99 (.003)	.97 (.006)	.99 (.004)	.99 (.004)
Incongruent	.96 (.010)	.05 (.010)	.93 (.013)	.96 (.008)
Low WMC				
Neutral	.99 (.005)	.99 (.006)	.99 (.005)	.99 (.005)
Congruent	.99 (.003)	.99 (.006)	.99 (.004)	.99 (.004)
Incongruent	.97 (.010)	.96 (.012)	.96 (.013)	.98 (.008)

The two-way interaction of SOA and WM Capacity was marginally significant, $F(1, 58) = 2.87$, $p < .10$. Low WM individuals showed poorer performance on trials with short SOA than on trials with long SOA, $F(1, 58) = 10.28$, $p < .01$. High WM participants were not influenced by variation in the length of the SOA (*F* < 1.00). For low WM participants, a short SOA reduced performance strongly in shift trials, *F*(1, 58) = 6.91, *p* = .01, the small difference in stay trials was not significant, *F*(1, 58) = 1.57, *p* > .10.

5.3.3 Attentional Network Test

We carried out a 4-level Cue condition (no, center, double, spatial cue) × 3-level Flanker type (neutral, congruent, incongruent) ANOVA with WM capacity as between subject factor. For the accuracy data, the main effect of WM capacity was significant, *F*(1, 58) = 3.88, *p* = .05. High capacity individuals performed the task more accurately relative to low WM capacity individuals (see Table 5.1). No further effects involving WM capacity were significant. Since accuracy was ceiling for low and high WM capacity individuals, our focus will be on the RT data.

Table 5.2. *Means of the median RT (milliseconds) and standard deviations of participants with high and low WMC in each condition of the ANT as assessed in Experiment 1.*

	Cue			
Flanker	No	Center	Double	Spatial
High WMC				
Neutral	553 (14)	510 (14)	507 (13)	463 (12)
Congruent	550 (15)	506 (13)	512 (12)	467 (12)
Incongruent	643 (21)	615 (22)	603 (20)	540 (21)
Low WMC				
Neutral	574 (14)	532 (14)	532 (13)	471 (12)
Congruent	567 (15)	525 (14)	522 (12)	473 (13)
Incongruent	677 (21)	667 (22)	651 (20)	570 (21)

ANOVA of the RT data were based on mean median RTs for correct trials only. Mean RT data are displayed in Table 5.2. The interaction between flanker and WM capacity approached significance, *F*(2, 116) = 3.26, *p* < .07, ε = .60. Individuals with low WM capacity showed a larger difference between compatible and incompatible trials, *F*(1, 58) = 4.04, *p* < .05, indicating that the WM groups differ in executive attention. No further comparison yielded significance (*F*s<1.00).

We further calculated two separately one-way ANOVAs for the alerting and orienting function with WM capacity as independent factor. Alerting was calculated as difference between mean median RT of the double and no cue condition and orienting by subtracting the mean median RT of the spatial cue condition from mean median RT of the center cue. Individuals with high and low WM capacity did not differ in altering, *F* < 1.00, but in orienting *F*(1, 58) = 4.72, *p* <.05. As can be seen in Figure 5.5, we observed a larger difference for low than high WM capacity individuals between center and spatial cue conditions. Note that the executive control component defined as difference between congruent and incongruent trials was already quantified in our post-hoc analyses of the significant WM capacity and flanker interaction.

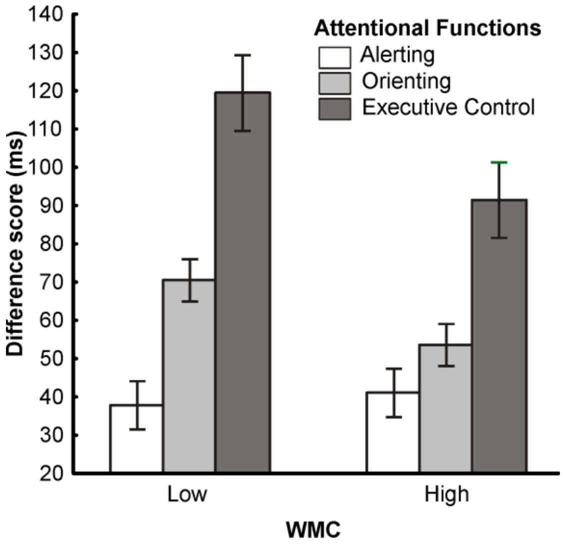

Figure 5.5. *The ANT difference scores for high and low WMC groups as obtained in Experiment 1; the error bars represent plus or minus one standard error of the mean.*

5.4 Discussion

In Experiment 1 we set out to investigate attention control and its contribution to understanding individual differences in WM capacity. In order to do so, we assessed each participants WM capacity and divided participants into two WM capacity groups. Participants completed further a battery of attention task, the cued categorization task and the ANT respectively. We hypothesized that individuals with low WM capacity would be less efficient in orienting attention to target stimuli. For both attention tasks, we found evidence for this hypothesis. For the ANT, differences between WM capacity groups were seen in the orienting network, which was interpreted to reflect individual variations in target selection. For the cued categorization task, we found low WM capacity individuals to perform less accurately on shift trials compared to baseline trials. By contrast, no such effects were found for those participants with high WM capacity. These were the predicted findings. Low WM participants seem to be less efficient in engaging attention on relevant information and they seem to need more time to set up this function than the high WM group. Unexpectedly, in stay trials low WM participants also showed poorer performance than at baseline and the effect was as large as in shift trials with long SOA.

A possible reason for this reduction in accuracy in stay trials is that low WM participants are generally less efficient in situations requiring controlled attention. In fact, in stay as well as shift trials correct task performance depends on the cue, and thus, in both conditions cognitive control is necessary to specify the appropriate task requirements upon the cue. If this control process is impaired, performance is more error-prone. We reason that the requirement to specify the cue in our cued categorization task is similar to continuous performance tasks (Braver & Barch, 2002; Cohen & Servan-Schreiber, 1992) or context-updating tasks (Lenartowicz, 2010), a specific version of the continuous performance task in which the context specifies the next to-be-performed action. In the standard version of the continuous performance task, participants view a continuous stream of letters and respond to a specific target. For example, in the AX variant of the task, participants should detect the target letter “X” with a certain button press only when it follows the letter “A”. For all other letters, including an “X” that is not preceded by an “A” (BX trials), participants should react by pressing another button. The AX trial is usually the most frequent one. Thus, the correct reaction on the target letter X is contingent of the context provided by a cue (A letter or no A letter). Redick and colleagues (Redick & Engle, 2011; Redick, 2014) very recently used this task to explore the relationship between WM capacity and the ability to use task context information to specify the task set. They found individuals with low WM capacity to make more errors in AX and BX trials relative to high WM capacity individuals. In other words, only high WM participants behaved adaptively and they used the task context to specify the target response in advance. This is similar to our cued categorization task in which the location of the to-be-categorized target is contingent on the cue. A cue first has to be evaluated specifying the actual task set, i.e. “do nothing and stay at the actual position” or “shift attention to the opposite side”. If this explanation is correct, low WM participants would not be especially slow in voluntarily initiating attention shifts, but more generally in specifying task sets for cognitive control.

Additionally, stay and shift trials in the cued categorization task were presented in a mixed order, so that for each trial the appropriate task sets have to be coordinated and constantly adapted in correspondence to the current task demands. This requires to retrieve or reactivate the new task set and to inhibit the irrelevant one whenever the task requirements have changed. Thus, one aspect that influences the ease of task set specification is whether individuals are efficient in resolving the conflict between the current task set and the irrelevant one. According to the controlled-attention view (see Chapter 4.1) we would expect individuals with high WM capacity to be more effective in doing so. This is exactly what our results of the executive attention function assessed in the ANT promote – a function of attention which is assumed to reflect online response-competition. Specifically, we found individuals with low WM capacity to be slower in resolving the response conflict than their high WM capacity counterparts. In our cued categorization task, we observe an analogous competition. The occurrence of the cue elicits task set competition and requires further attentional control in form of higher executive functions to resolve this conflict. In this view, the faster individuals are in resolving conflicts of competing responses, the better they should perform in our cued categorization task. Thus, individual variations in WM capacity seem to be most evident in situations where there are multiple distractors and/or a prepotent behavior that conflicts with the desired target behavior. This effect has also been demonstrated in Stroop tasks, wherein participants are instructed to name the ink of the color the word is written in. Here, WM capacity differences were found to be associated with Stroop interference (Hutchison, 2011; Kane & Engle, 2003; Morey et al., 2012). For instance, Kane and Engle (2003) varied the proportion of trials being congruent in ink and color in Stroop tasks. The largest differences in errors between high and low WM capacity groups on the incongruent trials were found when most of the trials were congruent in ink of color and word. More precisely, the proportion of congruent Stroop trials did not affect performance of high WM capacity individuals. In contrast, low WM capacity individuals made more errors on incongruent trials when the amount of congruent trials was high.

Given these differences between high and low WM participants with regard to the ability to specify and coordinate task sets, it is possible that the results of Experiment 1 go back to the necessity of reconfiguring the task set (stay or shift) upon task contexts (the cue) on a trial-by-trial basis. This hypothesis will be investigated in Experiment 2 of this dissertation project.

6 Experiment 2: The Influence of Task Set Reconfiguration Processes

6.1 Introduction

Experiment 1 delivered several indications that low WM capacity individuals might show deficits in reconfiguring appropriate task sets. In other words, the differences in WM capacity found in our cued categorization task might not per se reflect individual differences in voluntarily orienting attention towards relevant stimuli to bias them for privileged processing, but may reflect differences in the ability to specify and coordinate changing task demands. In Experiment 1, stay and shift trials were presented in a mixed order, so that for each trial the appropriate task set had to be monitored, and if needed, reconfigured for adequate task performance, so the deficit of low WM capacity individuals could indeed reflect deficits in task set reconfiguration. Such reconfiguration processes include the selection, implementation and coordination of a set of specific processes (Meiran, 1996). The main aim of Experiment 2 was to evaluate this hypothesis.

In theory, each task requires the configuration of mental resources or task sets (Jersild, 1927; Rogers & Monsell, 1995). This concept refers to the ability to configure an appropriate set of processes in accordance to task requirements. Task sets include representations of relevant objects, reactions and corresponding S-R mappings. Thus, selective attention mechanisms are conceptually incorporated in task sets

(Vandierendonck, 2014). By definition no more than one task set can be active at the same time. If multiple tasks are to be completed, a reconfiguration or switch process of task set settings is required (Olivers & Meeter, 2008) including the adaptation of cognitive processes in face of environmental changes. This coordination process is often referred to as cognitive flexibility and is proposed to be function of cognitive control (Miyake et al., 2000).

Imagine a person performing a discrete task. On some trials the task changes (switches) and on others the task remains the same. Each task requires an appropriate configuration of mental resources. The efficiency with which we perform the task depends on the flexibility that allows the rapid implementation of the appropriate task set when needed. If the task changes, the old task set must be suppressed and the new task set activated. As a result, reconfiguration costs arise. This effect has been extensively studied in task switching paradigms. Here, performance on single task blocks, were participants perform the same task, is better compared to mixed blocks, where task demands change on a trial-by-trial basis. This has been taken as evidence for global task set reconfiguration costs (see Monsell, 2003 for a review). Recently, Liefooghe, Barrouillet, Vandierendonck and Camos (2008) revealed that a reduction of performance in a WM task can indeed be induced by the introduction of a task switching requirement. They completed a series of experiments where they implemented task switching in continuous complex span tasks (see Chapter 2.1 for task description). The results revealed that the number of recalled stimuli declines when the amount of task switches increases. “As WM capacity is assumed to be limited, either task may suffer from the overlapping task execution, at least to the extent that both call on the shared resource” (Vandierendonck, 2012, p. 230). Thus, it might be expected that performance in a dual-task design is reduced whenever there is a second task that taps into the same process. For example, in our cued categorization task performance might suffer because selecting the appropriate task set based upon the cue and selecting the target might both tax the same resources.

In order to investigate whether our findings in Experiment 1 are due to global task set reconfiguration costs or deficits in voluntarily engaging attention to targets, we implemented single blocks consisting of either stay or shift trials in our procedure. If low WM capacity individuals are not generally less efficient in controlling the allocation of attention, but are limited in their ability or willingness to reconfigure task sets in any given trial, we should find no or smaller individual differences on single task blocks. That is, low and high WM capacity individuals should perform equally well. However, if individuals differ in the ability to execute allocation of attention voluntarily, we would expect identical costs in single stay and shift blocks as in the mixed block. Additionally, in the mixed block we increased the proportion of stay trials compared to shift and baseline trials. As stated in Chapter 5.4 (Kane & Engle, 2003; Redick, 2014) low WM capacity individuals are less likely to respond according to task requirements when the habitual response is predominant in the task context. In the cued categorization task, stay trials, i.e. keeping the attention at the attended location, can be considered to be associated with the more habitual reaction. Hence, increasing the number of these trials should make the task more demanding and magnify differences in the abilities of attention control.

Furthermore, in Experiment 2 we increased the motivation to make use of the cue before the target is presented. The presentation duration of the target array in Experiment 1 was very long which provided individuals with sufficient time to solve the task by a reactive strategy. From this account, individuals might not have exclusively used the cue information in advance to orient attention towards the target location prior to the onset of the target display but might have used memory of the cue at a late point in time when the target was already presented. If participants remember the cue and its location, they can reactively infer which of the two squares was indicated as target. That this possibility exists may reduce the motivation to proactively orient attention upon the presentation of the cue. We took a number of actions to increase this motivation: We decreased the presentation duration of the target array, we masked the target, and we made the perceptual task more demanding so that orienting attention prior to the onset of the target display is the most efficient strategy.

6.2 Method

Except as noted below, all details were identical to Experiment 1. Participants took part in a similar cued categorization task alongside different change detection tasks. Again we changed task order across participants. For the current purpose only the cued categorization task is of central relevance and will be described in the following.

6.2.1 Participants

From those participants that completed all assigned tasks in Experiment 1, we recruited 41 participants. Six participants were excluded owing to accuracies below chance in the cued categorization task of Experiment 2. All analyses were conducted on the remaining 35 participants (age range = 18-35 years, *M* = 23.63, 23 female). All participants were compensated for their time with 8€ per hour for their participation.

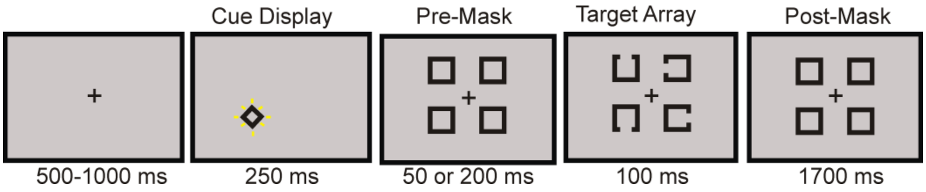

Figure 6.1. *Example of experimental procedure of Experiment 2. Depicted is a shift trial.*

6.2.2 Stimuli

All stimuli were presented at the corners of an imaginary polygon within 2.8° × 2.4° region on the monitor and contained a visual angle of 0.8°. We changed the stimulus material into Landolt Cs. Unlike colors, Landolt Cs are more complex stimuli and require focal attention at the time of presentation to process them correctly. One target was accompanied by three competitors. Before and after the probe array, squares were displayed as masks.

6.2.3 Procedure

The basic procedure remained the same as in Experiment 1 but the targets were changed (see Figure 6.1). In this task version targets were Landolt Cs and each target was accompanied by three competitive items. Subjects were required to identify the orientation of the cued item at a single spatial location (at the same position as the cue or at the horizontal opposite side of it, depending on the identity of the cue). Shortly before the onset and after the offset of the target display, four placeholders (squares) were displayed. The presentation duration of all displays remained the same as in the cued categorization task of Experiment 1 except for the duration of the target array, which was reduced to 100 ms. On baseline trials a green fixation cross was flashed for the same duration time as the cue in the center of the screen. The response was delivered by pressing the button on the response pad that matched the orientation of the Landolt C which was currently the target. Participants performed three blocks: One stay, one shift and one mixed block. At the beginning of each block, participants were given several practice trials. The task order of the three experimental blocks in the cued categorization task was counterbalanced in an ABC-CAB-BCA design between subjects, respectively.

Within each single block, participants completed twenty trials. For the mixed block, thirty stay trials, twenty shift trials and twenty baseline trials were presented randomly mixed.

6.3 Results

We used the same *K* scores as in Experiment 1 to estimate individual variations in WM capacity. Based on a new median split, participants were divided into high and low WM subgroups with mean *K* scores of 4.69 (*SD* = .53, range 3.90-5.70) and 3.17 (*SD* = .53, range 2.00-3.80) for high and low WM individuals, respectively.

6.3.1 Cued Categorization Task

The analogous analysis as Experiment 1 was conducted for the mixed block condition. The pattern of results is summarized in Figure 6.2. The two-way interaction of SOA and WM capacity was marginally significant, $F(1, 33) = 3.14$, $p < .09$, $\eta_p^2 = .09$. Again, whereas, high WM individuals performed equally well independently of SOA ($F < 1.00$), low WM individuals improved their performance at long relative to short SOAs, $F(1, 33) = 10.44$, $p < .01$. Again, this effect is mainly due to shift trials.

For low WM capacity participants, a short SOA impaired performance strongly in shift trials, $t(33) = 4.16$, $p < .01$. Compared to Experiment 1 high WM capacity individuals also performed less accurate on shift trials with a short SOA, $t(33) = 1.72$, $p < .05$, but the impairment was still smaller compared to low WM capacity individuals, $t(33) = 1.90$, $p < .05$. The differences between the long and short SOA for shift trials tended to be greater for those participants with low WM capacity relative to those with high WM capacity, $t(33) = 1.89$, $p < .07$.

The second analysis was conducted to examine individual differences when it was not necessary to coordinate or reconfigure different task sets. If the effects found in the mixed blocks are caused by task set reconfiguration costs, we should find no or smaller capacity-related individual differences in single task blocks. The pattern of accuracy is shown in Figure 6.3.

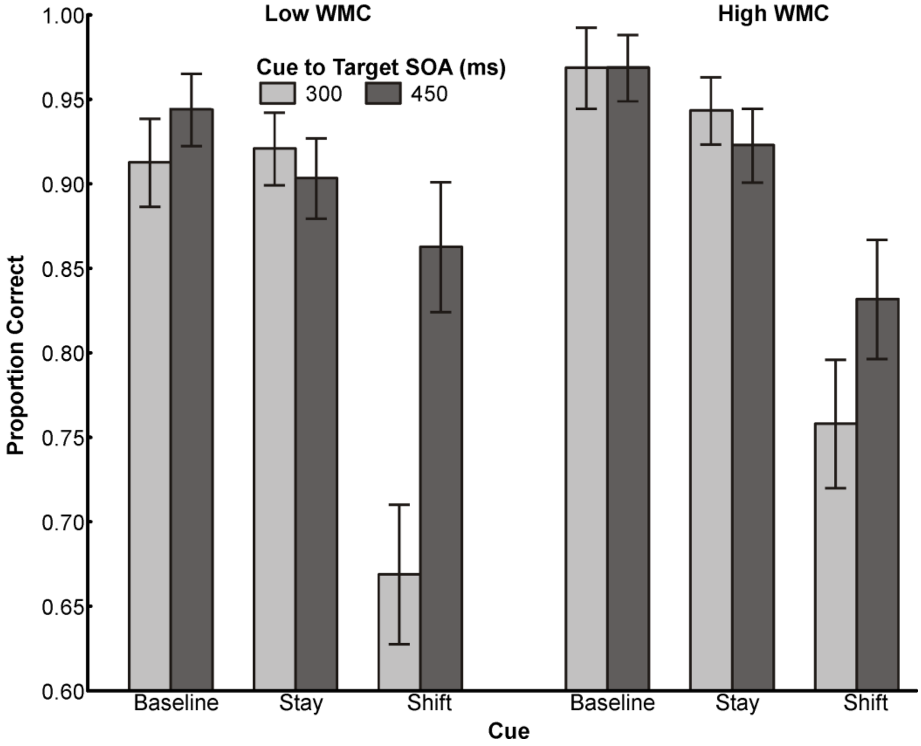

Figure 6.2. *Accuracy data in the cued categorization task of Experiment 2 as a function of cue and SOA for both WM capacity groups; error bars represent plus or minus one standard error of the mean.*

First, we entered accuracy on stay blocks in an ANOVA with SOA (300, 450 ms) as within subject factor and WM capacity (low, high) as between subject factor. There were no significant effects or interactions (largest *F*-value *F*(1, 33) = 1.47, *p* = .23). The analogous analysis was done for single shift blocks. It revealed a significant main effect of SOA, *F*(1, 33) = 8.34, *p* < .01, indicating greater accuracy on trials with long than short SOA. Although the interaction was not significant, the main effect for SOA goes mainly back to low WM participants. Low WM participants performed less accurately on trials with short than long SOA, *t*(33) = 2.51, *p* < .01. Although we found the same tendency for high WM participants, *t*(33) = 1.54, *p* < .07, the reduction in accuracy with short SOA tended to be smaller relative to low WM participants, *t*(33) = 1.46, *p* < .08. An additional planned comparison between performance in shift trials on single compared to mixed blocks revealed that performance on single shift blocks is clearly higher regardless of SOA and WM capacity, *F*(1, 33) = 19.65, *p* < .01.

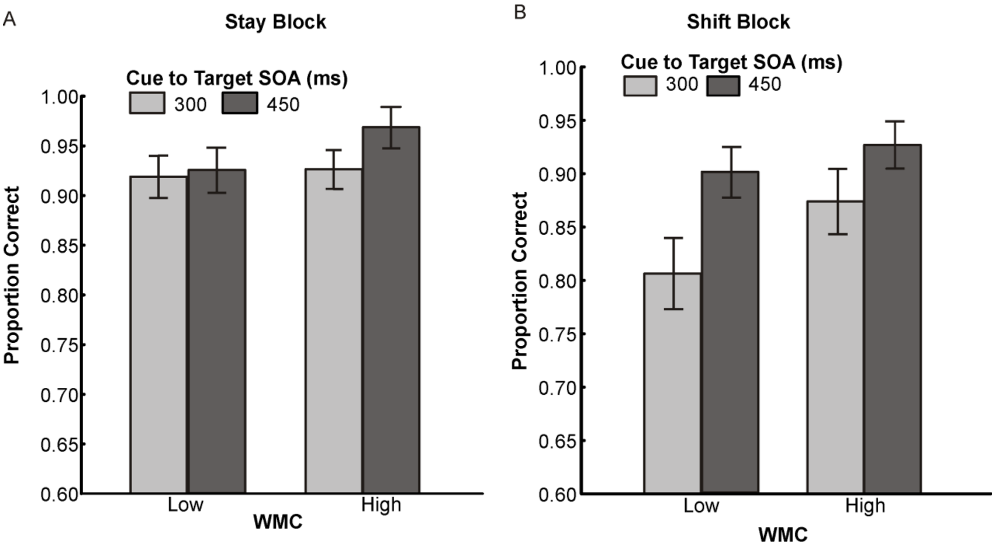

Figure 6.3. *Accuracy data as a function SOA for both WM capacity groups in single blocks of Experiment 2; error bars represent plus or minus one standard error of the mean.* ***A*** *Accuracy pattern in the stay block* ***B*** *Accuracy data in the shift block.*

Since in Experiment 2 we also found costs for high WM capacity in shift (as opposed to only stay) blocks, we conducted a post hoc comparison of costs in shift trials for Experiments 1 and 2. Figure 6.4 summarizes the time dependent shift trial costs, which were calculated as difference in performance between long and short SOA. In Experiment 1 as well as in the mixed block of Experiment 2 low WM capacity individuals showed larger costs in performing shift trials relative to high WM capacity individuals (Experiment 1, *t*(33) = 1.69, *p* < .05; mixed block Experiment 2, *t*(33) = -1.90, *p* < .05). By contrast, in the single shift block of Experiment 2 the same tendency was seen but it was reduced and no longer significant, *t*(33) = -0.82, *p* > 10. These results indicate that individual variations in WM capacity related to voluntarily engaging attention are more pronounced in conditions where different functions of cognitive control (target selection and task set coordination) have to be executed.

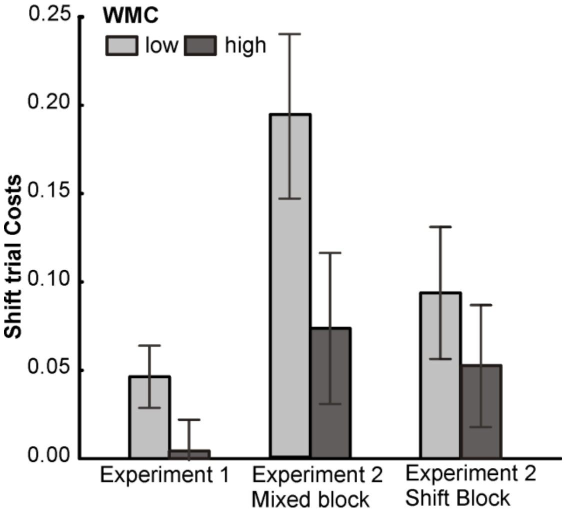

Figure 6.4. *Mean difference in shift trials for high and low WM participants of Experiments 1 and 2 (Standard error of means in parentheses). Shift trial costs have been calculated as difference in shift trials between long and short SOA. Positive values indicate costs.*

6.4 Discussion

The main aim of Experiment 2 was to specify whether or not general task set reconfiguration costs contributed to reduced performance of low WM capacity individuals obtained in the cued categorization task of Experiment 1. Participants therefore underwent trials with single and mixed trial order. For the mixed task set, we replicated our previous finding from Experiment 1 that low WM capacity individuals take longer to voluntarily allocate attention (shift trials). However, with the longer interval between cue and target display low WM capacity individuals were able overcome these costs. Unexpectedly, we now also found costs for high WM participants on shift trials. Compared to Experiment 1, the task requirements in this variant of the cued categorization task prohibited alternative task solving strategies, such as retroactively inferring which square was indicated as target. This suggests that if the task structure is more demanding, high WM capacity individuals also come at cost. Nevertheless, relative to participants with low WM capacity the time dependent costs were much smaller for high WM capacity individuals. Furthermore, and more importantly, performance in shift trials on single compared to mixed block was much better. When the entire block could be processed with the same task set, no time dependent differences in shift trial costs between high and low WM capacity individuals on single blocks were present. This supports our hypothesis that if the task demands did not require task set reconfiguration processes, individual differences involving WM capacity were reduced.

By definition task rules set up the frames for cognitive control processes that perceptual and categorical filter are later operating on (Bundesen, 1990). If participants are prepared that competitors for limited processing resources might appear, they boost processing of the task relevant items so that they win the race for representation. In contrast, the gate should be closed when a competitor has been selected (Olivers & Meeter, 2008). Thus, setting up a proper task set should facilitate item selection in the face of interference. In our cued categorization tasks the change in task set was explicitly signaled by a cue. If the task set still needed to be adapted before a proper response could be initiated we would expect more inaccurate performance on trials with short SOA. This was exactly what we found for participants with low WM capacity on shift trials. Note that, on stay trials updating the task set was not required for accurate performance. Behavior guided by the proper task rule or prepotent response would have led to the same response.

Before cognitive control can operate, the need for its intervention has to be detected (Botvinick, Braver, & Barch, 2001). Recently, Liesefeld et al. (2014) could show such a link between the initiation of higher executive control and the detection of control demands. More importantly, the magnitude of the implementation of executive control was positively correlated with WM capacity and negatively with the amount of irrelevant information being stored. Thus, we hypothesized that one central mechanism associated with the implementation of cognitive control, is the detection and activation of task set reconfiguration and that variations in WM capacity could be explained in terms of differences in latency of this configuration process. Experiment 2 supported this idea. In conditions where no task set reconfiguration was required, costs in voluntary selection processes were reduced. In the next part of the thesis, we further developed the idea whether deficits in cognitive flexibility are associated with individual differences in efficient WM functioning by investigating individual differences in unnecessary storage costs.

It is important to note that, individual differences in the ability to reconfigure task sets cannot account for all WM capacity related effects we found in Experiment 2. On single shift blocks, wherein there was no need to reconfigure the task set, accuracy in trials with short SOAs was still reduced to greater extent as for those individuals with low relative to high WM capacity, supporting the idea that individual differences in WM capacity are also correlated with variations in the efficiency of orienting attention towards task relevant information. Thus, we believe that the differences in WM capacity found in mixed blocks of our cued categorization tasks are reflective of individual differences in orienting attention and coordination changing task requirements.

We have thus far interpreted our findings such that participants with low WM capacity were less effective to employ voluntary control processes and they were also slower in doing so compared with those participants with high WM capacity. An alternative view considers our results in the context of attentional disengagement. According to this perspective, the pattern of findings might not exclusively depend on differences in voluntary engagement of attention, but rather in the time individuals need to disengage attention once it has been captured (in this case by the cue). In our cued categorization task, attention must be clearly engaged and oriented towards the cue in order to process its information. This is true for both stay and shift trials because in both cases, participants have to use the information of the cue to voluntarily allocate attention to the target's location. Only in shift trials, however, individuals are required to disengage their focus of attention from the cue first to allocate their attention towards the target. Thus, the necessity to disengage attention from its current position goes hand in hand with voluntarily engaging attention to targets.

In Chapter 5 we have already reviewed that especially low WM capacity individuals are limited in rapidly disengaging attention from processing information when it has been engaged by a specific stimulus (Cashdollar et al., 2013; Fukuda & Vogel, 2011). However, individuals with high and low WM capacity do not always differ in the magnitude of attention capture. In both Cashdollar et al.'s and Fukuda and Vogel's studies the disengagement effect was not shown on just any information but only when the distractor shared the target defining feature, such as color. Those distractors that were presented in different colors did not slow down attentional disengagement. Thus, individual differences in WM capacity were only associated with delayed disengagement upon target feature contingent capture. The time attention is engaged on a specific stimulus depends critically on the attributes for which attention is set (e.g. Folk et al., 1992; Folk & Remington, 2006). According to this logic, congruent cues on the target's selection property should produce disengagement cost only. This was not the case in our cued categorization task. Here, the target defining feature was its position and in the shift condition cue and target never shared the target defining property, because target and shift cue were never displayed at the same location. In other words, although participants needed to engage in the processing of the cue information, and as a consequence in shift trials disengage their attention first from the cue’s position, the magnitude of this effect should not differ between high and low WM capacity individuals. Thus, we believe that our findings of Experiment 1 and 2 are reflective of individual variations in orienting attention towards targets rather than disengaging it from the cue.

Part 3

Cognitive Control and Unnecessary Storage in Working Memory

7 Cognitive Control Processes in General

Cognitive control is of central importance in everyday activities. For example, when we are driving to work in the morning, we have to plan the best route, but flexibly change the route when the street is suddenly blocked due to road works. All these different subtasks must be monitored and solved appropriately to ensure that we arrive on work in time. Even carrying out simple actions like making a cup of coffee necessitates a set of effective cognitive operations such as putting coffee instead of a tea bag into the mug or boiling the water before pouring it into the cup together with the coffee. Without question, such actions require setting and carrying out goals and to avoid being distracted by competing alternatives. Cognitive control processes are assumed to ensure this. They operate in service of task sets and refer to a wide range of mental operations and strategic processes to ensure goal-directed behavior. This is what Baddeley and Hitch (1974) called central executive, and what Norman and Shallice (1986) labeled the supervisory attention system. Thus, specific processes, such as cognitive flexibility or selective attention, can be functionally integrated into the broader concept of cognitive control (Miyake et al., 2000).

The complexity of cognitive control is most evident when we make mistakes. For example, when we go into the kitchen to make a cup of coffee and end up doing something else instead or when we pick up our coat to go out when the phone starts ringing and then end up going out without our coat on. Given the broad impact of cognitive control, deficits in cognitive control might account for many types of failures within the cognitive system. From this viewpoint, lapses in specific attentional processing components like selective attention might be a result of the absence of cognitive control in general rather than deficits in within its specific components. The question of whether lapses in selective attention are due to deficits of cognitive control in general or more specific aspects within cognitive control (e.g., engagement of attention) and its relationship to individual differences in WM capacity and effective WM functioning will be more deeply evaluated in this part of the thesis.

Briefly stated, we investigate whether optimal WM functioning is associated with the ability to monitor and coordinate the implementation of the correct task set or the ability to operate on specific elementary selection processes. We reason that individual variations in WM capacity are reflective of general abilities to exert cognitive control rather than variations within specific processes. In fact, attention as well as WM are assumed to rely on general cognitive control processes (Engle & Kane, 2004; Kane & Conway, 2007). Evidence for this, was revealed in several types of cognitive tasks with minimal memory requirements but high demands on cognitive control. As detailed in Chapters 5 and 6, it has been found that association between WM capacity and selective attention are most pronounced whenever the current task goal competes with the more habitual response (Hutchison, 2011; Kane & Engle, 2003; Redick & Engle, 2011; Redick, 2014; Unsworth et al., 2004). Our results of Experiment 2 extend this idea by showing that variations in WM capacity are associated with the specific ability to control the attentional allocation towards relevant information and the general ability to flexibly switch and coordinate changing task demands.

Engle et al. (1999) even go further and suggest that any WM task also contains components of cognitive control like blocking interference or other aspects of controlled attention. In the next chapter, we develop three different possibilities of the role of cognitive control in performing change detection tasks with distractor-present trials as described in Chapter 4.2 and analyze how modulations of cognitive control contribute to a better understanding of individual differences in WM capacity.

7.1 Neglected Interactions of Cognitive Control Processes in Change Detection Tasks

Previously, it has been shown that individuals with high and low WM capacity differ in their ability to control what information will be maintained in WM (Jost et al., 2011; Liesefeld et al., 2014; McNab & Klingberg, 2008; Vogel, McCollough, et al., 2005). People who are able to retain more objects in WM are also more efficient in gating relevant items. However, we believe that these findings may require a more complex explanation. In accordance with Engle et al. (1999) we argue that adding distractor-present trials in a standard change detection task increases the involvement of cognitive control in general. Thus, variations in unnecessary storage costs – an indicator for optimal WM functioning – might be reflective of variations in different cognitive control abilities. We see at least two different components of cognitive control involved while performing change detection tasks and we will describe the dynamic interplay in the following.

The Influence of Cognitive Flexibility

First, in the standard change detection task with selection demands (Jost et al., 2011; Liesefeld et al., 2014; Vogel, McCollough, et al., 2005), participants in different trial types in principle have to perform two different tasks. In one task, participants are required to select a subset of relevant items out of an array consisting of relevant and irrelevant items while on the other task no selection processes are required and all items must be stored. Each task is associated with a certain task set defining the appropriate processes. However, by definition only one task set can be active at a certain time and people have to continuously switch back and forth between those (see Chapter 6.1; Olivers & Meeter, 2008). Thus, another way of looking at the study design is from a dual-task perspective. From this perspective, changing demands require flexibility of cognitive control processes and participants show costs in performance whenever the task set must be alternated. Since the frequency of distractor-present trials is lower relative to pure-target trials, performance costs due to task set coordination should be most evident in distractor-present trials. From this viewpoint, it is likely that the general ability to switch efficiently between different task sets might contribute to unnecessary storage costs as described above.

Central to the ability of task set reconfiguration is whether the task change can be anticipated or if it comes by surprise. Typically, the more time people have to prepare for an upcoming task switch, the less costs on performance are found (Meiran, 1996). Furthermore, and more importantly, it has been shown that when participants know prior to the target display which task they are required to execute, performance sharply increases (Meiran, Chorev, & Sapir, 2000). However, in the standard change detection task with distractor-present trials the actual task set can first be identified when the-to-be memorized stimuli are present. Only at this point participants are able to discriminate between trials where selection processes are relevant or not. Thus, the timing of task set reconfiguration strongly depends on the distractors' presence itself and its detection. In other words, in order to stop the processing of distractor items, their presence has to be detected first. Recently, Liesefeld et al. (2014) found evidence for such a causal chain of the initiation of selection mechanisms and the timing of distractor detection in a change detection task. Furthermore, and more importantly, individuals with high and low WM capacity differed in the time needed for distractor detection, with low WM capacity individuals taking longer in doing so than high WM capacity individuals. In this view, unnecessary storage costs should be reduced when participants know which task to execute prior to the onset of the memory array. We addressed this question in Experiment 3.

Controlling for Different Dynamics of Cognitive Control

In Experiment 4 we further evaluated whether unnecessary storage costs are not due to the fact that participants need to coordinate two task sets per se, but rather due to the amount of cognitive load that causes increased interference from irrelevant distractors. This question taps into different dynamics of cognitive control. According to Lavie and colleagues' load theory of selective attention (Lavie, Hirst, de Fockert, & Viding, 2004; Lavie, 2005, 2010), selective attention consists of two mechanisms: an early, passive and a second goal-directed mechanism. The latter one ensures that attended but irrelevant information does not enter WM and is considered to be an active, cognitive process. However, its effectiveness depends on cognitive load. If cognitive load is high and most of a person's cognitive capacity is consumed, only few resources are left for selective attention. Thus, distractors might be privileged for processing and enter WM. A person, however, is more efficient in controlling goal-directed processing of relevant stimuli in situations under low cognitive load. Thus, the larger the cognitive load, the less efficient selective attention operates. This effect has been found for different types of load (Lavie et al., 2004).

For instance, there is a high load on cognitive control when people are engaged in dual-tasks. Here, people have to switch constantly between different task sets. If the task demands changes, the old task set must be suppressed and the new task set and its corresponding processes are activated and initiated (Rogers & Monsell, 1995). This coordination process imposes a high load on the general cognitive control component of cognitive flexibility. Studies using such load manipulations have revealed that interference of irrelevant distraction as measured by response competition is larger in condition with high cognitive load (Lavie et al., 2004). It has further been shown that a reduction on performance in a WM task (complex span task) increases as a function of the number of task switches (Liefooghe et al., 2008). Hence, imposing load on cognitive control like it is the case in multi-task coordination decreases the effectiveness of selective attention. Both processes therefore seem to recruit the same resources. In Experiment 2 of this dissertation project, we could further show that the magnitude of target selection costs is not only modulated by cognitive load but is also associated with individual differences in WM capacity. More precisely, we found that load on cognitive control in form of the requirement of task set coordination (as in mixed vs. single task blocks) reduced to a greater extent the efficiency of selective attention for low than high WM capacity individuals (see Chapter 6).

This raises the question whether optimal WM functioning is modulated by cognitive load, with higher cognitive load leading to unnecessary storage of irrelevant information. Thus, selection mechanisms can only operate upon their full potential if processing resources are still available. In change detection tasks with distractor-present trials the size of cognitive load is high. People are required to monitor and coordinate different task sets (cognitive flexibility) as well as to initiate specific selection mechanisms (target selection), if needed. Important in this respect is that both processes share the same resources, but that the processing of distractors can only be stopped if the appropriate task set has been previously activated. If most cognitive resources are already consumed at the moment of target selection by task set specification, only few resources are left to stop distractor processing. In this view, any drop in WM performance in distractor-present trials would be because both control processes – task set coordination and target selection

– push cognitive control to its limits. Thus, reducing load on cognitive control processes in general should lower unnecessary storage costs in WM performance. From this view, optimal WM functioning might depend on the availability of overall cognitive control functions at the moment of selection.

Testing the Influence of Speed of Cognitive Control

Closely intertwined with the relationship between task set reconfiguration and selective attention is the sequential organization of both processes. Before selection mechanism can be initiated, the accurate task set has to be reactivated. From this view, the timing of selection processes depends strongly on the speed of task set coordination. Any delays in task set reconfiguration would impede selective attention, therefore causing greater interference. Evidence from a dual-task paradigm with varied intervals between cue and stimulus presentation supports this idea. Here, reduced task switching costs have been found with prolonged cue-stimulus intervals, indicating that task set coordination takes time (Meiran, 1996; Rogers & Monsell, 1995). In Experiment 2 of this dissertation project we could further show that WM capacity is correlated with individual differences in the speed of this coordination process. The group differences we uncovered suggest that low WM capacity individuals take more time in task set reconfiguration compared to high WM capacity individuals (as in mixed vs. single task blocks; see Chapter 6). In Experiment 5, we set out to investigate whether variations in speed of task set configuration are associated with differences in WM capacity.

8 Experiment 3: Cognitive Flexibility and Unnecessary Storage Costs

8.1 Introduction

The ability to process or select relevant information at the expense of irrelevant information is critical for adequate WM functioning. As detailed in Chapter 4, WM has a very limited online capacity. Thus, one important aspect of efficient WM functioning involves controlling what information is maintained, by prioritizing task relevant information consistent with current task goals. Cognitive control is assumed to operate in service of these task goals. If individuals are less efficient in implementing the reconfiguration of appropriate task sets, the initiation of specific attentional processes associated with a certain task set will be delayed. In fact, in a typical change detection task with distractors, both processes are closely intertwined. As detailed in Chapter 7.1, at the onset of the memory array the implementation of the appropriate task set will be initiated. However, that is the same time when the corresponding selection processes are already required. Therefore, any deficits in reconfiguring the appropriate task set might impair the initiation of selection processes in distractor-present trials and increase interference. Moreover, it has been shown that individuals with high and low WM capacity differ in the ability to set the appropriate task set upon task contexts (see Chapter 5.4; Hutchison, 2011; Kane & Engle, 2003; Redick, 2014), with low WM capacity individuals taking longer to specify it relative to high WM capacity individuals (see Chapter 6.4; Liesefeld et al., 2014). A critical issue, therefore, concerns whether the efficiency of WM functioning can be improved by contextually aiding task set reconfiguration processes. The main aim of Experiment 3 was to explore whether unnecessary storage costs in low WM capacity individuals are due to such deficits in coordinating different task sets – especially if the task demands are high – rather than selection mechanism per se. Specifically, we wanted to evaluate whether unnecessary storage costs in low WM capacity individuals can be reduced by allowing participants to set the appropriate processes prior to the onset of the memory array. We recorded behavioral and electrophysiological data to analyze selection efficiency in high and low WM capacity individuals.

The experimental procedures we used were similar to previous ERP research investigating the influence of selective attention on WM performance (Vogel, McCollough, et al., 2005). On each trial, a bilateral memory array containing of different colored rectangles were presented briefly. On some trials, the targets were displayed among distractors. After a retention period, memory was tested by showing a single item per side, and the participants had to state whether this item was different or the same as the item at corresponding position in the memory array. We used single-probe arrays in order to reduce comparison processes in the task which are assumed to take place when the test array contains the whole array (Kyllingsbaek & Bundesen, 2009).

To disentangle the role of coordinating changing task requirements and initiating selection mechanisms, we used a cueing paradigm with different predictive cue types. One cue type just signaled which side of the sample array should be remembered (direction cue). This cue type served as baseline. Performance on the task was then compared with conditions where the cue type was assumed to reactivate the task set in advance by indicating whether or not distractors would be present. In this condition, a colored cue was assumed to act as exogenous retrieval cue to reactivate the task set before the presentation of the memory array (Waszak, Hommel, & Allport, 2003). In particular, we used colored pre-cues as task set reactivation cues. Previous studies on predictive cues have already shown improved WM performance following different types of predictive cues (Griffin & Nobre, 2003; Linke, Vicente-Grabovetsky, Mitchell, & Cusack, 2011; Murray et al., 2011; Schmidt, Vogel, Woodman, & Luck, 2002). For instance, Schmidt et al. (2002) found advantageous effects for WM storage for cued relative to uncued locations. This was even the case when the cued location was not more likely to be probed at the test array. More recently, Li and Saiki (2015) further investigated the influence of different cue types (color, location) on WM performance. For instance, in their experiment 2 they showed beneficial effects for colored pre-cues compared to location pre-cues in a change detection task. Prior to the onset of the memory array a color or location pre-cue appeared. Color cues indicated a possible change in color at the same location and location cues a location change of the same color stimuli as presented in the memory array. In order to avoid an instruction bias, participants were told to remember both independent of the cue type. They found that WM performance was more accurate after color cues than location pre-cues, indicating that colored pre-cues are more efficient in modulating WM performance than location pre-cues.

Drawing upon these findings, we used colored pre-cues displayed in the target color as task set reconfiguration cues. We reasoned that the implementation of task set cues reduces the load of cognitive control engaged in task set coordination for two reasons. First, the task set cue alerted people to prepare for the upcoming trial type (distractor-present vs. distractor-absent) before the presentation of the memory array. Furthermore, and more importantly, displaying the task set cue in the target color refreshed the task goal (remember the stimuli presented in the target color), and therefore was proposed to facilitate the processing of task-relevant information (Waszak et al., 2003). Thus, comparing trials with and without task set cues should allow us to disentangle the intertwined relationship between the efficiency of task set coordination (cognitive flexibility) and selection mechanisms. We hypothesized that if low WM capacity individuals are less efficient in task set coordination, we would observe increased WM performance in distractor-present trials after task set cues relative to sole direction cues. Alternatively, if unnecessary storage costs are a result of individual differences in selection processes per se, WM performance for low WM capacity individuals in distractor-present trials should be independent of cue type and no improvement after task set cues should be found. Note that for high WM capacity individuals we did not expect to find any unnecessary storage costs, and therefore the task set cue should have no influence.

A second aim of our study was to find electrophysiological correlates of the expected behavioral performance patterns. Specifically, we were interested in neural measures of optimal WM functioning and attentional selection. To measure electrophysiological correlates of WM capacity, we relied on CDA amplitude (see Chapter 3). Its amplitude has not merely been shown to be sensitive to the amount of information being stored and individual differences in WM capacity (Vogel & Machizawa, 2004) but seems also to be a powerful ERP component to examine how attention control directs the encoding of information into WM (McCollough et al., 2007; Vogel, McCollough, et al., 2005). In particular, because the amplitude of the CDA is sensitive to the number of items being stored, we can use it as an online measure of how much information is currently held in WM and compare the amplitude in distractor-present conditions with and without task set reactivation. As in previous studies, we expected to find unnecessary storage costs for low working memory capacity individuals reflected in CDA patterns. Specifically, we hypothesized that CDA amplitude in distractor-present trials should be the same as in the pure-target condition with the same amount of stimuli. However, in trials containing task set cues, when the reconfiguration of the appropriate task set could be done before the memory items appeared, we expected CDA amplitude in distractor-present conditions after task set cues to be attenuated relative to sole direction cues. For high WM capacity individuals, no unnecessary storage costs were assumed independent of cue type. Thus, CDA amplitude in distractor-present trials was always to be identical to CDA amplitude in trials in the pure-target condition but with the same amount of targets.

Finally, related to efficiency of selection mechanisms is the point in time efficiency of target selection is apparent We were particularly interested in electrophysiological correlates of attention to relevant and irrelevant stimuli during WM encoding. There is neural evidence that attention can influence sensory processing as early as 100 to 200 ms (P1/ N1). This has been documented in studies showing attentional modulation of spatial attention (Luck & Hillyard, 1994), feature selection (Zanto & Gazzaley, 2009) and whole objects (Rutman et al., 2010). Specifically, the N1 component seems not only to be sensitive to the amount of information being processed (Kursawe & Zimmer, 2015), but also to discrimination processes related to spatial as well as feature selection (Hillyard, Vogel, & Luck, 1998; Mangun & Hillyard, 1991; Vogel & Luck, 2000). Building on these findings, it has been established that early perceptual processes can already influence subsequent WM performance. In a study conducted by Zanto and Gazzaley (2009) it has been shown that early attentional mechanisms can indeed modulate attentional filtering. In their study, EEG was recorded while participants performed a serial change detection paradigm. The task contained four sequential apertures of dots:

two displays consisted of moving dots and two displays were colored but stable. Selective attention was manipulated by instructing participants to remember either the color or motion direction and to ignore the other stimuli respectively. The ERPs revealed significant early attentional modulation for color (N1) and motion (P1) stimuli. The peak of early attentional markers (P1/N1) was larger for relevant compared to irrelevant stimuli.

Interestingly, this effect was significantly attenuated for low compared to high performance trials suggesting that early attentional processes do influence WM performance. Based on these findings, we reasoned that the N1 component which is closely related to early attentional discrimination should be sensitive to deficits in selection processes related to WM capacity. We were particularly interested in the modulation of the N1 in the hemisphere contralateral to the target, because of the laterality of the visual system. That is, relevant items presented in one hemifield of a bilateral array should be neurally represented in the contralateral hemisphere. In particular, we expected the N1 amplitude in the distractor-present condition to be attenuated relative to the set size with the same amount of stimuli but all being targets. However, this should only be apparent for high WM capacity individuals. For low WM capacity individuals, by contrast, the N1 amplitude should be a function of number of stimuli, because we assumed a delayed initiation of selection mechanism due to ongoing task set reconfiguration processes. Thus, the N1 amplitude in distractor-present condition should be the same as pure-target trials with the same amount of stimuli. Since efficiency of task set coordination was assumed to be influenced by task set cues, we expected to observe an attenuation in the N1 component in distractor-present trials after task set cues for low WM capacity individuals. For high WM capacity individuals no extra reduction in N1 amplitude was expected.

Taken together, the major aim of this study was to address the possibility that selection costs on WM performance as found in previous studies might be influenced by individual differences in efficiency of cognitive control processes in terms of task set reconfiguration. We tested this idea by comparing task conditions where task set reconfiguration was aided or not.

8.2 Methods

8.2.1 Participants

Fifty volunteers from Saarland University were tested and paid eight Euro per hour for their participation. All participants in this and the following experiments were right-handed, had normal color vision (as verified by the Ishihara color vision test; Ishihara, 1972) and gave written informed consent according to the procedure. One participant was excluded due to experimental error. The data collection of one participant was terminated by the experimenter noticing he or she was too tired to proceed. Eight participants were excluded due to EEG artifacts. The final sample consisted of 40 participants (26 female) between 18 and 30 years old (*M* = 23.73).

8.2.2 Stimuli

All stimuli were presented against a black background. Cue items subtended a visual angle of 0.94° and were presented on the fixation cross. In total three different cue types were used. One cue type was displayed in light grey and only indicated the relevant hemifield (direction cue). The direction cue was realized for all set sizes and served as baseline. Two further cue types additionally contained the color of the targets (pink or yellow) and allowed to discriminate between trials with and without distractor at a very early stage of the trial procedure (task set cue). For set size two and five, an unfilled arrow drawn in the relevant color was shown, whereas in the distractor-present condition the arrow was completely filled with the relevant color.

Each memory item was a rectangle selected from a set of four distinct orientations (horizontal, vertical, +45°, -45°). The color of the stimuli was yellow and magenta and the assignment of color to targets or distractors was counterbalanced across participants. The stimuli appeared in a transparent square (0.65°×0.65°) on an imaginary circle with a radius of 3.5° around the center of the screen. Only lateral positions were used with the restriction that the closest position was 1.75° away from the perpendicular bisectors of the sides. In the right and left hemifield the same number of items was shown on the screen. Only one hemifield was relevant at a certain time and at the irrelevant hemifield fillers at the corresponding positions has been displayed. For the distractor-present condition, the fillers were displayed in the corresponding color relative to the relevant hemifield.

Test items were chosen out of the same set of stimuli as the memory items. At the test array, two probe items appeared. One probe item was displayed at the same position as the memory item which was about to be tested. The other one appeared at the irrelevant hemifield in relation to the probe item. On change trials, the probe item was different as the memory item.

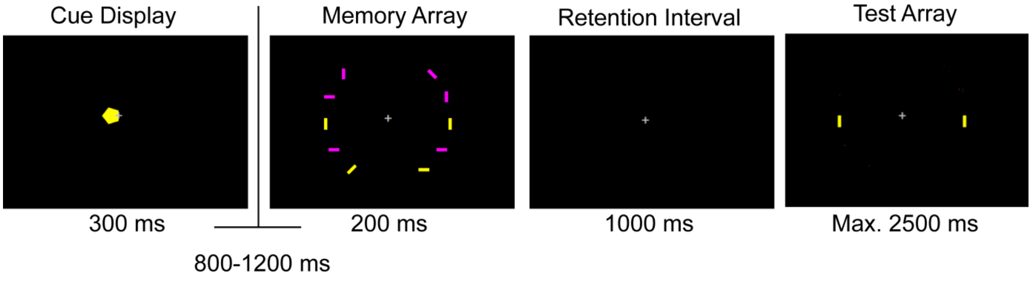

Figure 8.1. *Schematic illustration of the procedure of Experiment 3. Depicted is a distractor-present trial with task set cue.*

8.2.3 Procedure

Participants performed a visual bilateral change detection task (see Figure 8.1). Each trial began with central fixation. After a jittered delay of 300-500 ms, the cue display appeared for 300 ms. The cue was either predictive on the upcoming task set or only indicated the relevant hemifield. In 50% of the trials the cue pointed to the left or the right side, respectively. A blank fixation screen followed for a random time ranging from 800 to 1200 ms. The prolonged cue-to-memory interval, compared to previous studies (e.g.; Vogel, McCollough, et al., 2005), should guarantee that all sensory persistence of the cue was eliminated and would not influence early sensory markers of the memory display (Irwin & Yeomans, 1986). Then the memory array appeared for 200 ms consisting of either two targets, five targets or two targets and three distractors per side. After a retention period of 1000 ms (containing only the fixation cross), the test array appeared. The test display remained for 2500 ms or until the participants' response, whichever came first. To reduce comparison processes in the task which are assumed to take place when the test array contains the whole array, we displayed merely one object per side (Kyllingsbaek & Bundesen, 2009). Participants were instructed to detect an orientation change that occurred in 50% of the trials. The location of the test item was always congruent to its position in the corresponding memory array. Subjects pressed one button to indicate whether the test array was the same and another to state a difference. Participants were instructed to place priority on accuracy not speed. The assignment of response categories (match vs. no match) to the two buttons was counterbalanced across subjects. Responses were delivered via a Cedrus Response RB-834 pad. Participants were instructed to retain fixation on the cross in the center of the screen to avoid eye movements and to reduce blinks during the trial procedure. A inter trial interval of 2000 ms preceded the next trial. Here, the fixation cross was replaced by an X and participants were encouraged to blink preferably during this time.

At the beginning of the experiment, participants performed a minimum of 24 practice trials. Following practice, each session consisted of eighteen blocks. Each of these blocks consisted of a random mixture of different set sizes (2T, 2T3D, 5T) and pre-cues (direction, task set). In total participants performed 720 trials with 60 trials per condition consisting of 30 matching and nonmatching trials. Every 40 trials participants could take a short break. The whole experiment lasted about 90 minutes. In order to keep the motivation of the participants high during the experimental procedure, participants received feedback after each break indicating how accurately they responded overall. Additionally, in order to increase task engagement, two participants reaching the best performance were granted an additional 15€ for their participation.

8.2.4 EEG recording, pre-processing of EEG data and analyses

EEG was recorded from 32Ag/AgCl active electrodes (Acticap, Brain Products, Munich) mounted in an elastic cap. As locations for the electrodes a subset of the International 10-20 System (Fp1, Fp2, F7, F3, Fz, F4, F8, C3, Cz, C4, P3, Pz, P4, O1, O2) was used plus additional nonstandard positions mainly at the posterior and parietal sites (FC5, FC3, FCz, FC4, FC6, T7, T8, P7, P8, PO7, PO3, POz, PO4, PO8). The ground electrode was at AFz position. All sites were recorded with a left-mastoid reference and referenced off-line to the average of the left and right mastoids. Vertical and horizontal eye artifacts were monitored monocular with one electrode below the right eye and one at the outer canthi of the right eye. Correction of eye movements was done according to the method described by Gratton, Coles, and Donchin (1983). All impedances were kept below 10 kΩ. Signals were amplified with a DC coupled amplifier (Brain Amps, Brain Products, Munich, Germany). The sampling rate was 1000 Hz with an analog low-pass filter of 250 Hz. During data recording the active shield function of the Acticap-system was activated to suppress noise from the surrounding. To avoid reduction of amplitude of slow wave ERP components no high-pass filter was used.

All preprocessing and further analyses were completed using BrainVision Analyzer (Brain Vision, LLC). The EEG was segmented into epochs averaging from -200 to 1200 ms stimulus-locked to the onset of the memory array. Data were baseline-corrected with respect to the 200 ms pre-stimulus interval and off-line low pass filtered at 20Hz, 24 dB/octave to eliminate high frequency noise in the signal. Epochs containing artifacts, missing or incorrect answers were excluded from further analyses. Averages were computed for the different set sizes (2T, 2T3D, 5T) and cue types (direction, task set) but collapsed across matches and changes because we were interested in the retention interval. In this time period participants cannot yet discriminate between both conditions.

Since we were mostly interested in effects of attentional selection, the presented results are quantified on lateral parietal electrode pairs. We used visual inspection to quantify the electrode pairs where the effects of interest were most evident. This was the electrode pair P3 and P4. We extracted the CDA component as well as N1 component from this electrode pair.

We calculated contralateral and ipsilateral slow potentials for each electrode by averaging activity in a way that preserved the spatial positioning of the electrodes relative to the side indicated by the cue. Contralateral slow waves were calculated by combining activity over right electrodes when the relevant stimuli were presented in the left hemifield (and vice versa for the right hemifield). Ipsilateral slow waves were calculated by averaging activity over right (left) electrodes when the relevant stimuli were presented in the right (left) hemifield. We calculated the difference wave between ipsilateral und contralateral slow potentials to quantify the CDA. The time-window we entered in our statistical analyses was between 600-900 ms post memory array onset.

Furthermore, we quantified the amplitude on the visual N1 to the memory array as a peak-to-peak amplitude between P1 and N1. For P1 peak detection a time window of 90-180 ms was used, whereas for detection of the N1 peak amplitude the time window 160 – 260 ms was used. N1 amplitude was calculated for the contralateral slow waves, because we were only interested in attentional processes related to the hemisphere were the-to-be remembered stimuli are presented.

Behavioral and neural unnecessary storage costs were calculated as the difference between set size two and the distractor-present condition. Data were analyzed by a 3-level Set size (2T, 2T3D, 5T) × 2-level Cue type (direction cue and task set cue) × 2-level WM capacity (high vs. low) analysis of variance (ANOVA) with set size and cue type as repeated measures and WM capacity as between subject variable. Two-tailed t tests were used for post-hoc analyses. We applied Greenhouse Geisser adjustments for non-sphericity when appropriate. In this case, the uncorrected degrees of freedom, Greenhouse-Geisser coefficient (ε) and corrected probability levels are reported. Further, we will not report main effects whenever they are qualified by significant interactions.

8.3 Results

8.3.1 Behavioral

For analyses of performance, response accuracy corrected for guessing (PR) was calculated as proportion of hits minus proportion of false alarms for each set size and cue type (see Chapter 2.3 for further details concerning quantification). The PR-scores for different conditions are presented in Figure 8.2. WM capacity was estimated on the basis of a linear transformation of the PR-score for set size two and five (as described in Chapter 2.3; Cowan et al., 2005; Pashler, 1988). To make the results of our study comparable to other studies only trials with cues indicating direction were used to estimate each individual’s capacity. We took the maximum WM score from set size two or five as estimation of WM. The mean WM capacity estimate was 1.88 (SD = 0.44) ranging from .82 to 2.85. For further analyses participants were divided into two groups by a median split, high capacity (M = 2.17, SD = 0.38) and low capacity (M = 1.56, SD = 0.25) individuals respectively.

The ANOVA yielded a significant interaction effect between cue type and WM capacity, $F(1, 38) = 4.58$, $p < .05$, $\eta_p^2 = .11$; the interaction between set size and WM capacity approached significance, $F(2, 76) = 2.83$, $p = .08$, $\eta_p^2 = .07$, $\varepsilon = .72$. To follow up these interactions, we first analyzed unnecessary storage costs and compared unnecessary storage costs for high and low WM individuals, followed by a comparison of unnecessary storage costs between different cue types. We took the difference between PR-Scores of set size two and the distractor-present condition as indicator for unnecessary storage, since in both conditions the equal amount of targets was presented.

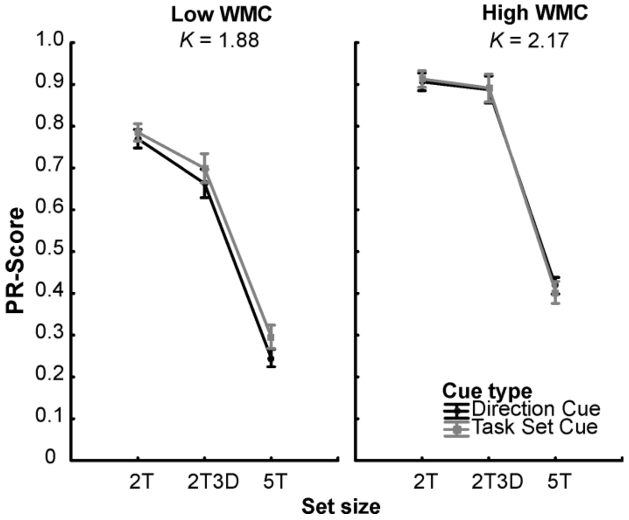

Figure 8.2. *Behavioral Results of Experiment 3. PR-Scores as a function of set size, cue type and WMC, error bars represent plus minus one standard error of the mean.*

First, we compared performance on trials with direction cues. As illustrated in Figure 8.2, high WM capacity individuals showed no unnecessary storage costs ($t < 1.00$). By contrast, performance for low WM capacity significantly dropped in trials with distractors ($t(38) = 4.42$, $p < .001$). The difference in the unnecessary storage quantified by individuals with high and low WM capacity was significant, $t(38) = 2.56$, $p = .02$. Next, we checked whether unnecessary storage costs for low WM individuals were reduced in trials with goal reactivation, as manipulated by the presence of the task set cue, compared to trials without goal reactivation (direction cue). Low WM capacity individuals significantly increased WM performance in the distractor-present condition with task set cues compared to trials with direction cues, $t(38) = 2.36$, $p = .02$. However, task set cues did not fully eliminate unnecessary storage costs. The PR-score in the distractor-present condition with task set cues was still lower relative to set size two and direction cues ($t < -1.99$, $p = .06$). For individuals with high WM capacity, performance in the distractor-present condition was the same independent of the manipulation cue type ($t < 1.00$).

8.3.2 Electrophysiology

The CDA waveforms for all different conditions are presented in Figure 8.3. The analogous statistical analyses as for the behavioral data were conducted. The interaction between set size and WM capacity was significant, $F(2, 76) = 4.19$, $p < .05$, $\eta_p^2 = .10$. To resolve this interaction, we first compared CDA amplitude between set sizes for conditions with direction cues only. For high WM capacity individuals, CDA amplitude for set size five was larger compared to set size two, $t(38) = 2.30$, $p < .05$. CDA amplitude for the distractor-present condition and set size two was identical ($t < 1.00$).

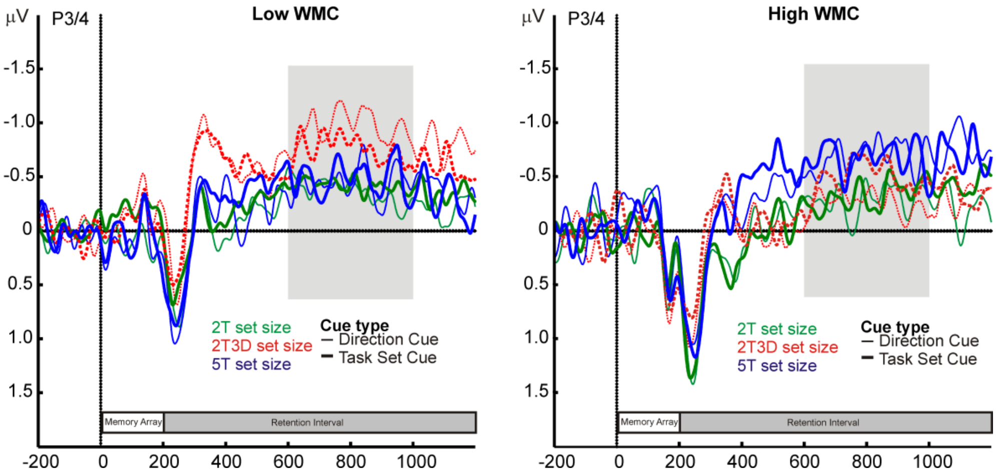

Figure 8.3 *Grand-averaged ERPs time-locked to the memory array of Experiment 3. Depicted is CDA amplitude as a number of set size and cue type for high and low WM capacity individuals. Note the negative direction of the y-axis Boxes highlight the time period of interest.*

These were the predicted findings and a replication of previous studies. By contrast, for low WM individuals CDA amplitude for set size five was identical to set size two ($t < 1.00$) and CDA amplitude for the distractor-present condition was larger compared to set size two, $t(38) = 2.21$, $p < .05$, as well as set size five, $t(38) = 2.21$, $p < .05$. For the cue type manipulation, no effects yielded significance.

Early processing stages were indexed by the N1 component as illustrated in Figure 8.4. The interaction between WM capacity and set size tended to be significant, $F(2, 76) = 2.58$, $p = .08$, $\eta_p^2 = .10$. As in previous studies, the N1 component was sensitive to the amount of sensory information being presented. That is, there was a significant increase in peak amplitude from set size two to set size five for both high and low WM capacity individuals, $t(38) = 4.67$, $p < .0001$, $t(38) = 2.41$, $p < .05$.

As can be seen in Figure 8.4, the peak amplitude for high WM capacity individuals was attenuated for the distractor-present condition relative to set size five and this reduction was significant, $t(38) = 2.70$, $p = .01$. This was not the case for participants with low WM capacity ($t < 1.00$). Moreover, the magnitude of the N1 modulation effect (difference between set size five and distractor-present condition) was different between the two groups, $t(38) = 2.00$, $p = .05$. The manipulation of cue type had no influence on the N1 component.

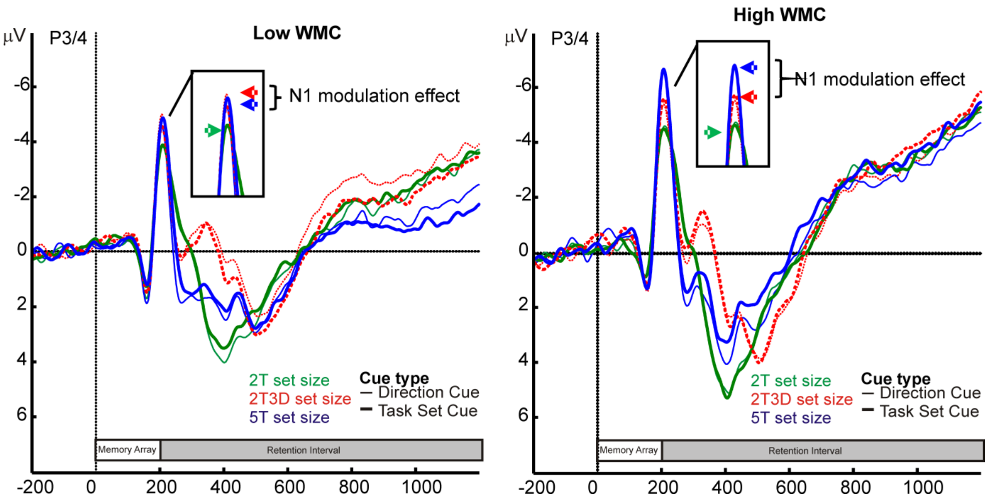

Figure 8.4. Grand-averaged ERPs time-locked to the memory array of Experiment 3. Depicted are the contralateral slow waves as a number of set size and cue type for high and low WM capacity individuals. The N1 modulation is the difference between distractor-present condition and set size five.

8.4 Discussion

Previous work highlighted that individuals who are able to retain more items are also better in controlling the filtering of irrelevant ones (Jost et al., 2011; Liesefeld et al., 2014; McNab & Klingberg, 2008; Vogel, McCollough, et al., 2005). However, the unnecessary storage of irrelevant information may not be due to deficits in specific selection mechanisms per se, but may be reflective of individual variations in the efficiency of cognitive flexibility related to WM capacity (see Experiment 2; Lavie et al., 2004). Our major aim was to test this hypothesis. Behaviorally, our results reflected the predicted findings. For high WM capacity individuals, we found no reduction in WM performance in the distractor-present condition relative to set size two, indicating that they were able to efficiently control the storage of relevant information. This finding was independent of cue type. By contrast, WM performance for low WM individuals was significantly impaired in distractor-present conditions relative to set size two indicating that they were unnecessarily storing more information than required. After the presentation of the task set cue, WM performance in distractor-present condition relative to conditions where the cue solely indicated direction was improved. However, some residual costs remained.

One possible explanation for such residual costs is that individuals with high and low WM capacity differ in both the coordination of task sets and the initiation of specific selection mechanisms, with low WM capacity individuals being less efficient in both processes. However, we believe that low WM capacity individuals are not per se less efficient in selection mechanisms. Alternatively, we reason that at the moment of target selection low WM capacity individuals might have already consumed most of their resource capacities. Thus, only few resources would be left to stop the processing of distractors and some distractors could have entered WM. Unnecessary storage costs after task set cues would not be abolished but reduced. Important in this respect is that selection processes can only be initiated when the appropriate task set has been reconfigured. This implies that cognitive control processes are at least to some extent sequentially organized and that cognitive flexibility and selective attention both share the same resources. This interpretation is supported by the load theory of selective attention developed by Lavie and colleagues (see Chapter 8.1; Lavie et al., 2004; Lavie, 2005, 2010). In this model, active selective attention processes are influenced by cognitive load. In conditions of high cognitive load, interference effects caused by irrelevant information are much more likely. This effect has been shown for different types of cognitive load, with dual-task coordination being one of them (Lavie et al., 2004). Therefore, this model might also apply to a change detection task with distractor-present trials being added. The mixed trial structure requires the cognitive system to switch flexibly between tasks where all items, or only a subset of items (distractor-present trials), are targets. Thus, cognitive load is high, especially in distractor-present trials where both cognitive processes – task set coordination and selection mechanisms – are required. Consequently, when a series of varying operations that load heavily on cognitive control, less time and resources are left for memory encoding and maintenance. If individuals with low WM capacity are generally less efficient in controlling limited cognitive resources, only few resources would be left for selection processes, which in turn causes greater interference from distractors. In Experiment 4 we further explored whether WM costs in distractor-present trials after task set reactivation cues are due to deficits in selection processes or the size of cognitive load. In order to make sure that at the moment of target selection resource capacities would be sufficient, we reduced set size. We further implemented pure, or single, distractor-present blocks. In single distractor blocks no additional demands on cognitive control besides selection are imposed. If our hypothesis regarding cognitive load is true, selection processes should operate on their full potential in single distractor blocks and under small set sizes.

A second aim of Experiment 3 was to find electrophysiological correlates for our behavioral results. As reflection of WM maintenance we used CDA amplitude. For participants with high WM we found the predicted findings. The amplitude of the CDA for set size two was identical to the distractor-present condition indicating that high WM capacity individuals efficiently controlled the gating of relevant information into WM. By contrast, for low WM capacity individuals the results of CDA amplitude were not in line with our predictions. Although CDA amplitude for the distractor-present condition was larger relative to set size two, the amplitude of set size five was reduced. In fact, CDA amplitude for set size five was identical to set size two. The latter aspect is in accordance with the slot model, if one considers that CDA amplitude should reach a stable plateau when set size reaches an individual’s capacity. Since the mean *K*-score of low WM capacity individuals was below two on the average no further increase of the CDA would be expected.

However, the CDA in the distractor present condition went more negative than in the other two conditions which contradicts the prediction. We therefore took a closer look at the slow potentials of which the CDA as a difference wave is calculated in order to check whether the distractor effect may be caused by ipsilateral effects. To ensure that no encoding effects are included in the analysis, we used a time window between 800 and 1000 ms. We found no significant difference at the ipsilateral slow potentials for low WM capacity individuals ($F < 1.00$; see Table 14.1), suggesting that increases in CDA amplitude in the distractor-present condition goes mainly back to more negative going contralateral slow potentials (see Figure 8.4). One possible explanation for this is that individuals were actually able to retain more items than CDA amplitude for set size five indicates. From this point of view, WM capacity in supra capacity set sizes would overload WM functioning and underestimate a person’s real capacity limits. Recent findings indicating an decrease in estimated WM capacity for low WM capacity individuals when the memory array contains high set sizes (Fukuda, Woodman, & Vogel, 2015; Linke et al., 2011) support this notion. Drawn upon this, we expected a more valid reflection of a person's real capacity limit, in Experiment 4 with reduced set sizes near to a person's capacity limit.

Furthermore, in Experiment 3 we aimed to test whether differences in efficiency of cognitive control are associated with the ability to utilize selection mechanisms at an initial stage of processing. We used the N1 component as an indicator for such early discrimination processes. Our analyses of N1 peaks showed that its amplitude increased with set size. The more visual information was presented, the larger the amplitude of the N1 (Ko et al., 2014; Kursawe & Zimmer, 2015). Importantly, its amplitude was modulated by WM capacity. High WM capacity individuals showed a clear attenuation of peak amplitude of the distractor-present condition relative to set size five, participants with low WM capacity did not. Both conditions displayed the same amount of visual information but differed in the amount of relevant items. The attenuation in amplitude in the distractor-present condition can be interpreted as an indicator for early attention selection mechanisms. It is consistent with previous findings and has been taken as evidence for the suppression of irrelevant information (Gulbinaite, Johnson, De Jong, Morey, & Van Rijn, 2014; Rutman et al., 2010; Zanto & Gazzaley, 2009).

However, task set cues relative to direction cues did not lead to a more effective prioritization of relevant information for individuals with low WM capacity. We found no differences in N1 peaks between set size five and the distractor-present condition independent of the cue type. One possible explanation is that early selection mechanisms are traits individuals high and low WM capacity differ in. Thus, the environmental context, such as task set cues, would have no influence on the efficiency of sensory target selection. Alternatively and in line with our previous argument, we reason that at the moment of initial target selection, the amount of cognitive resources left for distractor detection was not sufficient for individuals with low WM capacity. If this is true, low WM capacity individuals should be able to implement early selection processes when demands on cognitive control are reduced. In Experiment 4 we further evaluated this idea.

9 Experiment 4: Impacts of Cognitive Load

9.1 Introduction

As in Experiment 3, we were interested in comparing distractor-present conditions with and without early task set reactivation but with smaller set sizes lower than or close to the individual’s resource capacity. As we had reasoned, we may have found residual selection costs in participants with low WM capacity because task demands in Experiment 3 overloaded their cognitive functioning. Even task demands in the easiest task condition were already too high. We believe that the same argument accounts for the fact that we found no electrophysiological correlates of sensory target selection. In order to test this idea, we used an identical task design as in Experiment 3 with reduced set sizes. Pure-target trials only consisted of only one or three targets and distractor-present trials of one target and two distractors. We hypothesized that under conditions of low cognitive load (reduced set size and task set cues) low WM capacity individuals should show an improvement in performance and an attenuation in CDA amplitude in the distractor-present condition with task set cues relative to distractor-present trials with direction cues. For the N1 component we also expected an attenuation of the N1 component in distractor-present trials for low WM capacity individuals with task set cues. Our hypotheses for high WM capacity individuals were identical to those of Experiment 3. Additionally, we implemented single distractor blocks. The general logic was that in single distractor blocks the task context remains the same, so no additional strain on cognitive control was present besides the initiation of selection processes, and therefore cognitive load should be reduced. We argued that in single distractor blocks, no unnecessary storage costs should be found for both high and low WM capacity individuals because the task set does not have to be reconfigured, and thus, cognitive flexibility and selective attention mechanism at the moment of target selection would not overlap in first place. For the N1 component, we expected the same modulations as for those trials with task set cues for low WM capacity individuals. High WM capacity individuals were supposed to show an attenuation in the N1 component regardless of whether cognitive control was aided (task set cue, block) or not (direction cue).

9.2 Methods

Except as noted below, all details were identical to Experiment 3.

9.2.1 Participants

Twenty new subjects (10 female), between 18 and 33 years old, participated in this study.

9.2.2 Stimuli and Procedure

We reduced set size in the pure-target and distractor-present conditions. In the pure-target condition, participants had to remember one or three targets displayed in the target color (1T and 3T). In the distractor-present condition one target was presented among two distractors (1T2D). In order to avoid pop-out effects of the target singleton, the two distractors were displayed in different colors (e.g., pink or blue if the target color was yellow). Direction cues were realized for all set sizes. Task set cues, however, were constrained to distractor-present trials in mixed blocks only.

Each session consisted of six blocks. Three of these blocks consisted of a random mixture of different set sizes (1T, 1T2D, 3T) and cue types (direction cue and task set cue), and three blocks of trials only contained targets and distractors (1T2D). In these single distractor-blocks the cue only pointed either to the right or left direction and was never displayed in the target color. Half of the participants started with mixed blocks and half began with distractor blocks, and these were then alternated. In total participants performed 600 trials with all experimental conditions being counterbalanced. Every 24 trials participants could take a short break. The whole experiment lasted about 75 minutes. In order to increase task engagement, the feedback about correctness after each break was calculated from the preceding block.

9.2.3 Pre-processing of EEG data

The lateral posterior electrodes PO7 and PO8 were used to quantify the electrophysiological effects of interest. Here, the effects were most evident. However, similar patterns of activation were observed over neighboring electrode positions. For P1 peak detection a time window of 90-220 ms was used, whereas for detection of the N1 peak amplitude the time window 160-280 ms was used. The time window for CDA analyses was the same as in Experiment 3.

9.3 Results

Since sample size in Experiment 4 was smaller, we had fewer clearly high and low WM performers and therefore used repeated-measure analysis of covariance (ANCOVA) to quantify the influence of WM capacity on unnecessary storage costs and cue efficiency. In all analysis WM capacity was included as covariate. However, using a median split and calculating an ANOVA yielded to qualitatively analogous results.

9.3.1 Behavioral

The mean WM capacity was 2.03 (*SD* = 0.40) ranging from 1.32 to 2.67. We first analyzed effects of set size on WM capacity. We conducted an ANCOVA with 3-level Set size (1T, 1T2D, 3T) as within-subject factor, but included distractor-present trials with direction cues only. We excluded distractor-present trials of task set cues and single distractor blocks, because we expected performance in these conditions to be higher compared to direction cues, and therefore overshadow the predicted reduction in distractor-present trials for low WM capacity if cognitive control is not aided. The results are illustrated in Figure 9.1 A. The interaction between set size and WM capacity was significant, $F(2, 36) = 167.06$, $p < .001$, $\eta_p^2 = .09$. As in Experiment 3, performance in distractor-present trials compared to pure-target trials consisting of one target dropped significantly, $t(19) = 2.65$, $p < .05$, and, more importantly, the difference between distractor-present and pure-target trials correlated negatively with WM capacity, $r(20) = -.53$, $p < .05$, suggesting that low WM capacity individuals were unnecessarily storing also irrelevant items (Figure 9.1 B).

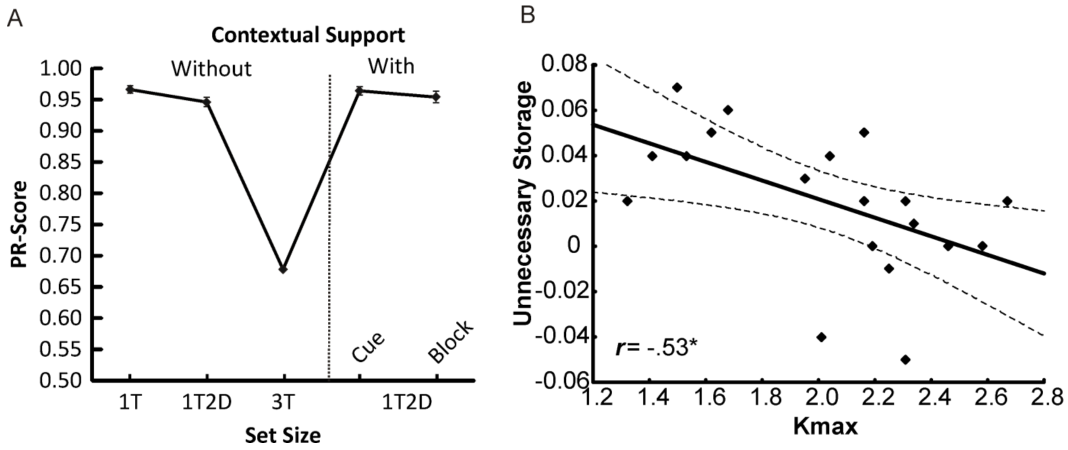

Figure 9.1. *Behavioral Results of Experiment 4.* ***A*** *PR-Scores as a function of set size and contextual support after controlling for WMC differences, error bars represent plus minus one standard error of the mean* ***B*** *Correlation between the unnecessary storage, as indicated by positive values, and WMC. Due to two visually inspected outliers we additionally used spearman rank correlation which is assumed to be insensitive to outliers. The respective correlation was* $r_{\text{Spearman}} = -.57$, $p < .01$.

Next, we checked whether performance improved in distractor-present trials when cognitive control was aided (cue, block) compared to distractor-present trials with direction cues which provided less support for cognitive control. In order to do so, we conducted an ANCOVA with 3-level Contextual support (Performance in distractor-present trials with support: single distractor-present block and task set cue vs. performance without support: direction cues). The interaction between contextual support and WM capacity was significant, $F(2, 36) = 3.41$, $p < .05$, $\eta_p^2 = .16$. Performance in distractor-present trials increased in conditions with contextual support (block or cue) compared to trials without contextual support (direction cues). This was mainly true for individuals with low WM capacity. That is, we observed a significant correlation between WM capacity and the difference in performance for distractor-present trials with sole direction cues and task set cues in mixed blocks, $r(20) = -.49$, $p < .05$; as well as a significant correlation between WM capacity and the difference in performance for distractor-present trials in mixed blocks with sole direction cues and performance in single distractor blocks $r(20) = -.47$, $p < .05$ (see Figure 9.2 A/B).

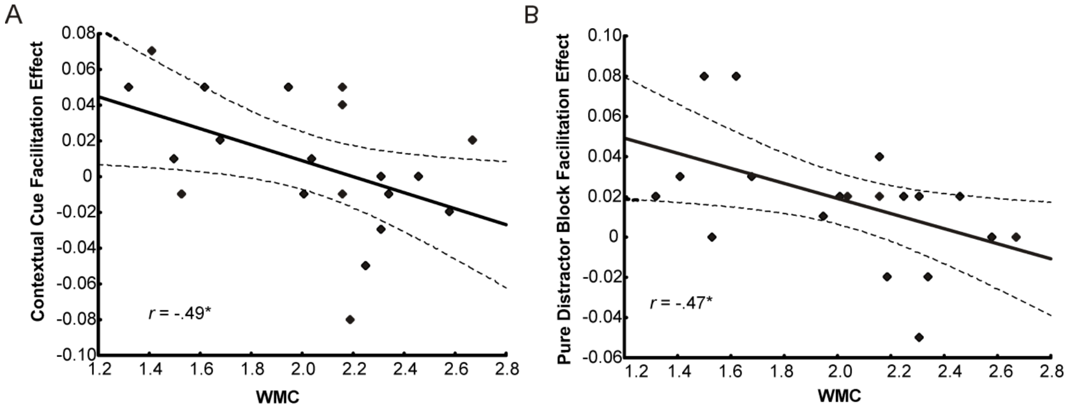

Figure 9.2. *Improvement in the distractor-present condition after contextual support relative to the distractor-condition without support of Experiment 4. Positive values indicate facilitation effects. Both correlations remain significant when using Spearman rank correlations (contextual cue facilitation effect, $r_{\text{Spearman}} = -.46$; pure distractor block facilitation effect, $p < .05$, $r_{\text{Spearman}} = -.51$, $p < .05$)* ***A*** *Facilitation effect after task set cues were obtained by subtracting performance in distractor-present trials with sole direction cues from performance in distractor-present trials with task set cues* ***B*** *Facilitation effect in single blocks were obtained by subtracting performance in distractor-present trials with sole direction cues from performance in distractor-present trials in single distractor blocks.*

9.3.2 Electrophysiology

The analogous analyses as for the behavior were conducted on the ERP amplitudes. For CDA amplitude, the interaction between set size and WM capacity approached significance, $F(2, 36) = 2.80$, $p < .10$, $\eta_p^2 = .13$, $\varepsilon = .67$. The amplitude of the CDA was larger for set size three compared to set size one, $t(19) = 4.20$, $p < .001$; and the distractor-present condition, $t(19) = 3.57$, $p < .01$. We found no differences between set size one and the distractor-present condition, $t < 1.00$. In contrast to Experiment 3, estimates of WM capacity were only poorly correlated with the electrophysiological reflection of unnecessary storage costs (difference between set size one and the distractor-present condition for direction cues), $r(20) = -.28$, $p = .24$.

Effects of contextual support tended to be significant, $F(2, 36) = 2.57$, $p = .09$, $\eta_p^2 = .13$. CDA amplitude was more negative after task set cues relative to direction cues, $t(19) = 1.79$, $p < .09$. This increase in CDA amplitude in comparison to direction cues correlated with WM capacity, *r*(20) = .40, *p* < .08, suggesting that low WM capacity individuals showed a larger difference than high WM capacity individuals (Figure 9.3 A).

As in Experiment 3, we further quantified this effect by analyzing slow potentials at hemispheres contralateral and ipsilateral to the target. For the ipsilateral hemisphere, we found a significant negative correlation between the increase in CDA amplitude after task set cues relative to direction cues and the decrease in amplitude of slow potentials, *r*(20) = -.66, *p* < .01. For the analogous comparison at the contralateral hemisphere, no effects were found, *r*(20) = .26, *p* = .27. These results suggest that the increase in CDA amplitude after task set cues is actually a reflection of better filtering of the irrelevant hemifield, and not the result of storing more items from the relevant hemifield, as one would assume.

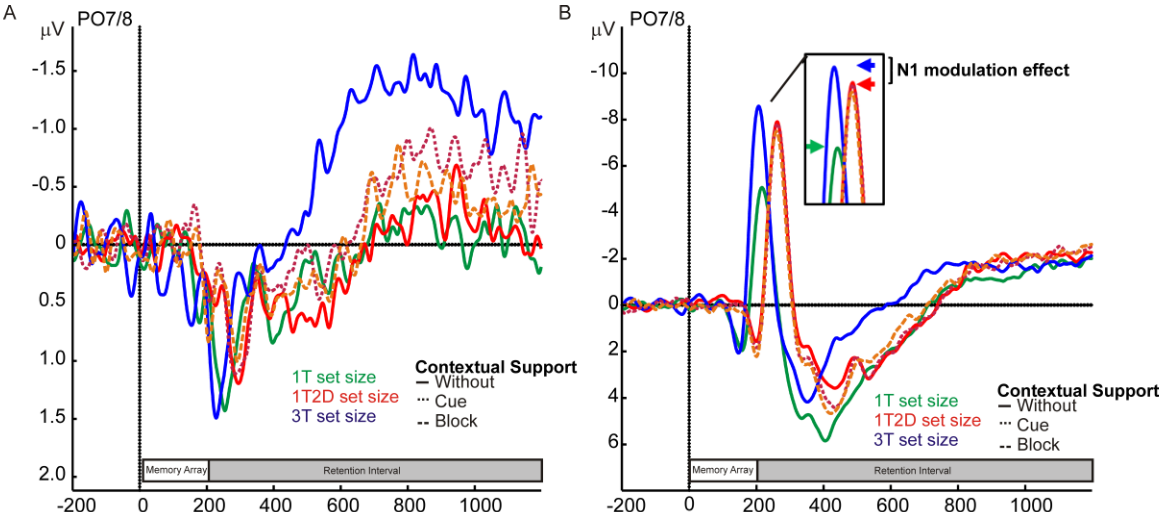

Figure 9.3. *Grand-averaged ERPs time-locked to the memory array of Experiment 4.* ***A*** *Depicted is CDA amplitude as function of set size and contextual support. Note the negative direction of the y-axis. Boxes highlight the time period of interest.* ***B*** *Depicted are the contralateral slow waves as a function of set size and contextual support. The N1 modulation is the difference between distractor-present condition and set size three.*

Analysis of the N1 component yielded a significant set size by WM interaction, *F*(2, 36) = 7.20, *p* < .01, η_p^2 = .29. The amplitude of the N1 component was influenced by the number of relevant stimuli being presented. Set size one differed significantly between the distractor-present condition and set size three (*t*(19) = 5.44, *p* < .001, *t*(19) = 7.13, *p* < .001). Moreover, the N1's peak for set size three was significantly larger compared to the distractor-present condition, *t*(19) = 3.83, *p* = .001. The magnitude of this attenuation effect of the N1 component was not correlated with WM capacity, *r*(20) = -.09, *p* = .71, suggesting that all participants applied early selection effects. No additional influences of contextual support were found (*F*s < 1.00). Note, that no effects on N1 latency yielded a significant interaction with WM capacity (Figure 9.3 B).

9.4 Discussion

The behavioral results of Experiment 4 concur with our previous findings of Experiment 3. WM capacity was associated with unnecessary storage costs. With increasing estimates of WM capacity, the amount of irrelevant information stored in WM decreased. Furthermore, and more importantly, when cognitive control processes were aided by activating the appropriate task set prior to the onset of the memory array (task set cue) or eliminating switching demands between different task sets (single distractor block), participants with low WM capacity significantly improved performance in distractor-present trials, with no difference between task set cue and single distractor block trials.

This effect was due to a better control of attention allocation. Specifically, after task set cues slow potentials at the ipsilateral hemisphere to the target were reduced. Thus, task set cues might not have modified the extent to which irrelevant information is suppressed per se but instead affected the spatial distribution of attention. Constraining attention to relevant information has the advantage that it increases the amount of resources allocated to information processing within the focus of attention (Eriksen & James, 1986) while outside the focus of attention less processing resources are allocated for processing (Handy et al., 2001; Lavie, 1995). In fact, there is accumulating evidence for an inability of low WM capacity individuals to effectively allocate attention on relevant information (Ahmed & de Fockert, 2012; Heitz & Engle, 2007). In bilateral arrays, items are presented in both hemifields and participants have to remember items in the relevant hemifield. If controlling the deployment of attention onto the relevant hemifield is what impedes individuals with low WM capacity, one would expect to find individual differences in electrophysiological reflections of the irrelevant hemifield. This is what Fukuda et al. (2015) recently observed. They analyzed slow potentials at hemispheres ipsilateral and contralateral to the target separately for high and low WM capacity groups. For the contralateral hemisphere, they found no individual differences in amplitude of slow waves. By contrast, they observed larger negativity at the ipsilateral hemisphere for individuals with low WM capacity relative to high WM capacity individuals. Thus, individuals with low WM capacity seem to be less efficient in allocating attention onto the relevant hemifield. As a consequence the irrelevant hemifield will be processed to a greater extent and irrelevant and relevant items compete for limited processing resources. This is especially likely under conditions of low load, such as when only one target is presented like in Experiment 4 (Arend & Zimmer, 2011). When load is low, it seems that attentional resources automatically process irrelevant environmental information. In distractor-present trials with task set cues, this effect seems to be reduced and individuals were better able to focus the allocation of processing resources on the relevant hemifield, and as a result, reducing load on item processing.

As in Experiment 3, the CDA amplitude dissociated from our behavioral results. We found no correlation between the electrophysiological reflection of unnecessary storage costs and our behavioral estimate of WM. Of course it might be the case that the behavioral improvements in WM performance after task set reactivation obtained in Experiments 3 and 4 do not reflect the extent to which targets are more efficiently encoded per se, producing less unnecessary storage of irrelevant items, but a result of more precise representation of the selected items. The higher the resolution of the memorized information, the easier is the later comparison process between the test item and the corresponding memory item at the test array. Such effects on comparison processes alone can in some cases explain behavioral WM capacity estimates (Alvarez & Cavanagh, 2004; Awh et al., 2007). Since the CDA amplitude is not sensitive to the precision of items being stored (Luria & Vogel, 2011), differences in item resolution could explain the dissociation between behavior and CDA of Experiments 3 and 4. However, we do not consider this a likely explanation. First, very recently it has been shown that cognitive control – the process which we have argued to underlie individual differences in WM capacity – did not affect the resolution of items in WM (Dowd, Kiyonaga, Beck, & Egner, 2015). Second, at the level of slow potentials we found evidence for improved attentional control due to increased efficiency in allocating attention away from information. In Experiment 4, for instance, we could show that the representation of the irrelevant hemifield in distractor-present trials was reduced after task set reactivation in the form of cues. It is therefore likely that the CDA is not a direct correlate or ’signature’ of memory storage (cf. also Postle, 2015) but a relative measure of the focusing and distribution of attention across the two hemifields which is related to but not identical to the number of stored items. Thus, instead of being constrained to focus on the difference in activity between ipsilateral and contralateral hemisphere (CDA amplitude), one might think of the utility of slow waves as electrophysiological correlate of WM storage. For instance, Arend and Zimmer (2012) found amplitudes of slow waves at the contralateral hemisphere to be more closely related to behavioral data than the CDA. The general role of the CDA and what implications slow potentials have for WM memory research will be more deeply discussed in Chapter 11.4.1 and Chapter 12 of the general discussion.

Finally, our results for the N1 component are consistent with the idea that individual differences in N1 modulation, as found in Experiment 3, reflect variations in the amount of cognitive resources left for distractor detection at the moment of target selection, rather than differences in early feature selection mechanisms per se (see Chapter 8.4). In Experiment 4 we observed no individual differences in sensory selection mechanisms, as the attenuation of the N1 component in the distractor-present condition was uncorrelated with WM capacity. Thus, in conditions of reduced cognitive load, high as well as low WM capacity individuals seemed to be able to allocate processing resources to relevant information. The manipulation of task set reactivation had no additional effect on this pattern.

10 Experiment 5: Testing the Influence of Reconfiguration Speed

10.1 Introduction

In Chapter 8 we argued that individual differences in WM capacity are associated with the efficiency of cognitive flexibility. One factor that overlaps with the ability to control the implementation of appropriate processes is the speed of this control process, and costs in dual-tasks have been proposed to reflect the speed of task set coordination (Rogers & Monsell, 1995). For instance, it has been shown that providing participants with sufficient time to reconfigure the task set prior to target presentation reduced switching costs (Meiran, 1996), indicating that task set coordination takes time. In Experiment 2 of this dissertation project, we could further show that WM capacity is correlated with differences in the speed of this coordination process, with low WM capacity individuals needing more time to do so than high WM capacity individuals (see Chapter 6). Our major aim of Experiment 5 was to evaluate whether individuals with high or low WM capacity differ in the speed of coordinating changing task demands (cognitive flexibility). In order to do so, we implemented two different cue-to-target SOAs in a change detection paradigm with distractors, a short and long SOA respectively.

We used a modified version of the bilateral change detection task of Experiment 4 based on the procedure described by McNab and Klingberg (2008). In this task version, participants performed a change detection task with memory arrays consisting of yellow and pink rectangles. Cues, given prior the onset of the memory array, were symbolic (geometric forms) and indicated if the presented stimuli were target stimuli and should be remembered (target condition) or whether yellow (or pink) rectangles should be classified as distractors and be ignored (distractor condition). Thus, in this current version of the change detection task, compared to Experiments 3 and 4, the memory array alone was not indicative of the current task set, because it always contained yellow and pink stimuli. The current task set could only be identified based on the cue's information. Thus, on any given trial the initiation of accurate processing steps needed to be implemented prior to the presentation of the-to-be memorized stimuli. As a consequence, all processes related to the identification and reconfiguration of appropriate task sets should be isolated from processes related to item selection. Critically, we manipulated the interval between cue display and memory array. We realized two different SOA, which, however, should be both long enough to evaluate the symbolic content (Wright & Ward, 1994). Thus, any time dependent effects related to differences in WM capacity could not be attributed to differences in the speed to classify the cue's information, but only to the ability to reconfigure the appropriate task set in the given time. The shortest SOA we realized in our study was set to 400 ms and we contrasted this with a longer SOA of 1000 ms. We expected performance of low but not high WM capacity individuals to be influenced by SOA. Specifically, we expected low WM but not high WM participants to show a reduction in WM performance in distractor-present trials relative to pure-target trials with the same number of targets (unnecessary storage costs) within the short SOA, so that SOA should influence performance only for low WM participants. With the long SOA, performance for low WM capacity individuals should be as accurate as for high WM capacity individuals. For high WM capacity individuals, no unnecessary storage costs were expected.

As in Experiments 3 and 4, on some of the trials cognitive control was contextually aided by task set cues in mixed blocks, or by single distractor blocks. Our hypotheses followed our previous results and the hypotheses of Experiment 3. For low but not high WM capacity individuals, we expected to observe unnecessary storage costs in trials without contextual support and no or reduced unnecessary storage costs in trials with contextual support. Since participants with high WM capacity were not expected to show any unnecessary storage cots, we did not expect any additional effects on contextual support for high WM capacity individuals. We had no specific hypothesis concerning the influence of SOA for trials with contextual support.

10.2 Methods

Except as noted below, the orientation change detection task in Experiment 5 was identical to Experiment 4. Participants additionally completed a color change detection task. Half of the participants began with the orientation change detection task and half with the color change detection task. However, to make results of Experiment 5 comparable to our findings of Experiments 3 and 4, all analyses are based on the orientation change detection task. Thus, the color change detection task will not be further reported.

10.2.1 Participants

Forty-eight Chinese volunteers (mean age: 22.71 years, range: 19-29, 24 female) participated in this experiment. They received 35 Yuan for their participation.

10.2.2 Stimuli

Cues subtended a visual angle of 1.17° and were presented in the center of the screen. As geometric forms, we used triangles and squares. The function of the cue was to indicate whether all items being displayed at the memory array should be remembered (pure target condition) or whether some of the stimuli needed to be ignored (distractor-present condition). The assignment of geometric shapes to pure target and distractor-present conditions was counterbalanced. As in our previous experiments, we implemented a task set cue for distractor-present trials in the mixed block. Here, the cue was presented in the target color on some of the trials.

Memory items were identical to Experiment 4. Each memory item appeared on an imaginary circle with a radius of 3° around the center of the screen. At the test display only one item appeared. This item was always displayed at the corresponding position of the tested memory item.

10.2.3 Procedure

The schematic of the experimental procedures is depicted in Figure 10.1. Responses were delivered via keyboards. Participants pressed one key to indicate a change and another key when test and memory item matched. The assignment of keys to this response categorization was counterbalanced across participants. Each session consisted of six blocks. Three of these blocks consisted of a random mixture of different set sizes (2T, 2T2D, 4T), cue types (pure-target cue, distractor-present cue and task set cue) and SOAs (400 ms vs. 1000 ms), and three blocks only contained targets and distractors (2T2D) and different SOAs (400 ms vs. 1000 ms). In these single distractor-blocks, no task set cues were realized. Half of the participants started with mixed blocks and half began with single distractor blocks, and these were then alternated.

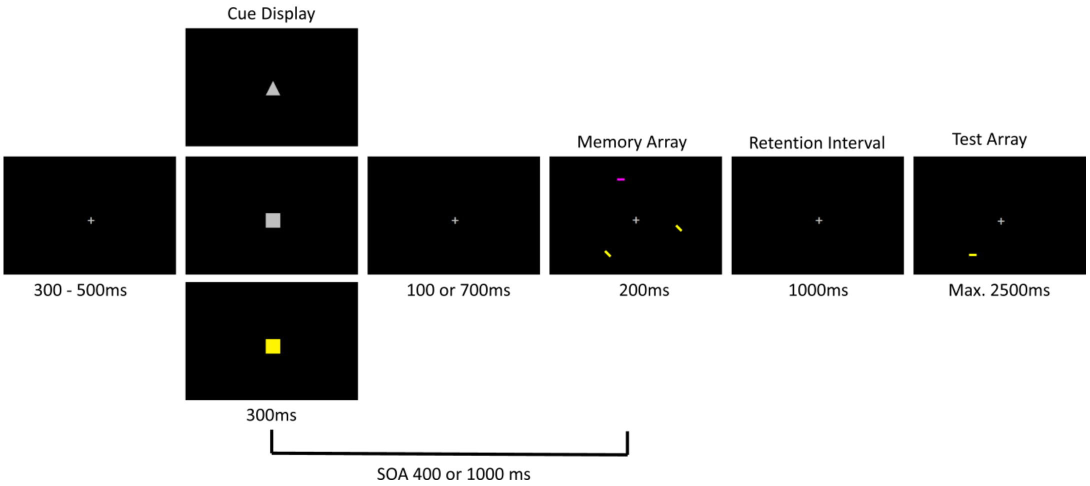

Figure 10.1. *Experimental paradigm of the distractor and pure-target condition in mixed block of Experiment 5. In this schematic a triangle indicated pure-target condition and squares distractor condition. The yellow square represents a task set condition.*

At the beginning of the experiment, the participants completed a minimum of 24 practice trials. In total participants performed 360 trials with 36 trials per condition consisting of 18 matching and nonmatching trials. Every 24 trials participants could take a short break. The procedure lasted about 45 minutes. In order to keep the motivation of the participants high during the experimental procedure, participants received feedback after each break indicating their accuracy in the preceding block.

We computed K_{max} as described in chapter 2.3. To make results of Experiment 5 comparable to previous studies only trials containing a short SOA were included.

10.3 Results

The mean WM capacity estimate was 2.69 (*SD* = 0.52) ranging from 1.56 to 3.76. Participants were divided into two groups by a median split, high capacity (*M* = 3.12, *SD* = 0.30) and low capacity (*M* = 2.32, *SD* = 0.35) individuals respectively.

We first calculated a three way 3 (Set size: 2T, 2T2D, 4T) × 2 (SOA: 400 vs. 1000) × 2 (WM Capacity: high vs. low) repeated measure analysis (ANOVA) with WM capacity as between subject factor to examine the effect of SOA on accuracy for the two WM capacity groups. For the same reasons as in Experiment 4 (see Chapter 9.3) we did not enter distractor-present trials containing task set cues or distractor-present trials of the single distractor block in this analysis. The ANOVA yielded a significant three-way interaction, $F(2,92) = 5.18$, $p < .01$. Figure 10.2 shows the PR-scores for each of the experimental conditions and both WM capacity groups. For low WM capacity individuals, the pattern of results was the predicted one. We observed reduced performance in the distractor-present condition relative to set size 2 on trials with short SOA, $t(46) = 2.84$, $p < .001$, indicating that individuals with low WM capacity were unnecessarily storing irrelevant information. At the longer SOA, however, performance in the distractor-present condition and set size 2 were identical, $t < 1.00$, suggesting influences of task set coordination speed on selective attention mechanism. Contrary to our expectations, individuals with high WM capacity also showed an analogous pattern of results to their low WM capacity counterparts. With short SOAs, WM performance declined in distractor-present trials compared to set size 2, $t(46) = 2.24$, $p < .05$, and with the longer SOA, no such decline in accuracy was found, $t(46) = 1.10$, $p = .27$.

Next, we evaluated effects of contextual support on WM performance in distractor-present trials. We calculated a three way 3(Contextual Support: no, task set cue, block) × SOA × WM capacity ANOVA. The interaction between contextual support and SOA approached significance, $F(2,92) = 2.45$ $p = .09$. No interaction including WM capacity yielded significance. However, visual inspection of the pattern of results suggests a differential relationship. For individuals with high WM capacity performance in distractor-present trials seemed to have reached its limits in distractor-present trials with long SOA, so that contextual support did not have any additional impact on performance. By contrast, it seems that low WM capacity individuals gained an additional advantageous effect in trials with long SOA, and particularly in the single distractor-present block. To further resolve effects of SOA and contextual support associated with WM capacity, we conducted follow-up *t*-test comparisons (*two-tailed*) for high and low WM capacity individuals separately. WM performance for participants with high WM capacity did not significantly improve at long SOAs independent of contextual support (all *t*s < 1.00). By contrast, for their low WM capacity counterparts we still found an improvement in performance at long SOAs (task set cue vs. no support, $t(46) = 2.62$, $p = .01$; block vs. no support $t(46) = 4.06$, $p < .0001$).

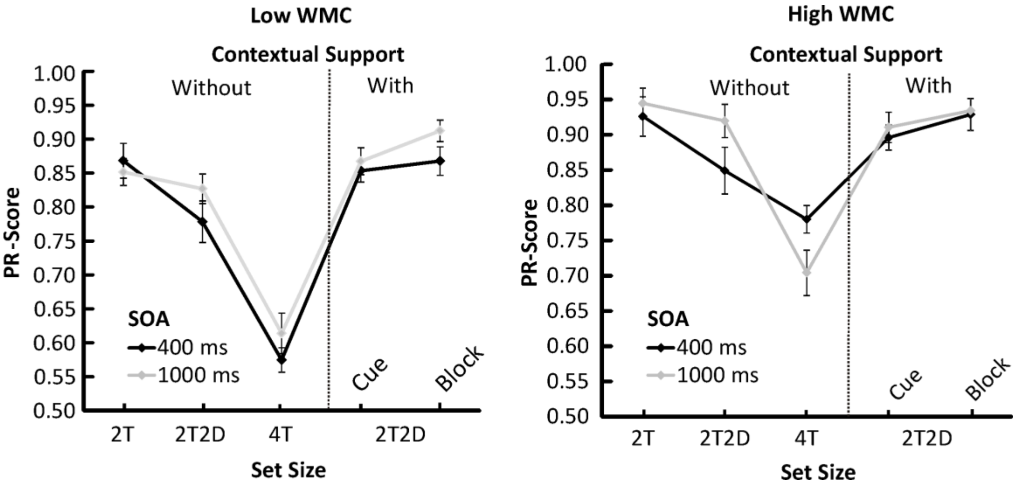

Figure 10.2. *Behavioral Results of Experiment 5. PR-Scores as a function of set size, contextual support and WMC, error bars represent plus minus one standard error of the mean.*

Overall, the results of Experiment 5 indicate that the magnitude of improvement in distractor-present trials was influenced by the size of unnecessary storage costs each individual showed. We quantified unnecessary storage costs as PR-Score of distractor-present trials without contextual support minus PR-Score of set size two in trials with a short SOA. This estimate was correlated with different improvements in performance in terms of contextual support. Improvements in performance were calculated as the difference between performance in distractor-present conditions for cue or block trials and distractor-present trials without contextual aid. Thus, positive values indicated facilitation effects. The results showed that the greater the unnecessary storage costs, the better the improvement from a short to a long SOA $r(48) = -.47$, $p = .001$, and the better the improvement after contextual support, as supported by two positive correlations between the amount of unnecessary storage in short SOA trials and the facilitation effect after either task set cues or blocked trials ($r(48) = .54$, $p < .001$; $r(48) = .73$, $p < .001$).

10.4 Discussion

The goal of Experiment 5 was to evaluate whether differences in speed of task set coordination are related to WM capacity and the unnecessary storage of irrelevant information. Specifically, we investigated whether prolonged reconfiguration processes account for unnecessary storage of irrelevant information for low WM capacity individuals. To assess this possibility, we conducted a modified change detection task which allowed us to disentangle task set reconfiguration processes and selection processes to a greater extent than Experiments 3 and 4. First, task instructions in form of cues indicated the task set validly prior to the onset of the memory items. Thus, processes related to the coordination of task components and encoding of relevant stimuli should not overlap. Second, we manipulated different SOAs to evaluate variations in speed of task set reconfiguration processes.

The results we observed provided mixed evidence for our hypothesis that variations in speed of task set reconfiguration are of central importance in accounting for individual differences in WM capacity. Although we did find reduced unnecessary storage costs with a long interval between cue and memory array compared to trials with a short one, we found the analogous pattern of results for high and low WM capacity individuals, suggesting that individual variations in WM capacity are not correlated with differences in speed of task set reconfiguration processes. However, this idea contradicts previous findings showing no unnecessary storage costs for high WM capacity individuals using an identical task design (McNab & Klingberg, 2008). One possibility is that the observation of an identical pattern of results for high and low WM capacity individuals in Experiment 5 is due to cultural differences between our sample and the ones reported in prior studies. There is recent evidence that indicates that individuals from Western and Asian cultures differ in perceptual and attentional processes. While Westerners tend to focus attention on relevant objects independent of context, Asians tend to process stimulus displays more holistically. That is, they allocate attention in a context-dependent manner by attending to stimuli and their relation to the context as a whole rather than focusing on particular stimuli only. Furthermore, and more importantly, Asians also store target objects in relation to their context and even remember more about this context information than individuals from western cultures (for a review see Nisbett & Miyamoto, 2005). Thus, if Asians are allocating attention differently than Westerners it seems likely that a distinction between high and low WM capacity based on remembering specific perceptual features is not as sharp as in our Western student populations of Experiments 1 to 4. However, to be sure that the results of Experiment 5 are indeed reflective of culture influences, we would need to repeat the same experiment within a western population and evaluate whether or not the pattern of results changes. An identical pattern of results in Western cultures would speak against cultural influences and against a correlation between WM capacity and speed of configuration processes. However, if, in contrast to our Experiment 5, low WM capacity individuals showed unnecessary storage costs with short SOA and high WM capacity individuals did not, our idea of cultural influences would be supported.

The same argument of cultural influences might also account for the fact that in Experiment 5, we observed large declines in the size of unnecessary storage costs with contextual support, for both high and low WM capacity individuals. This result seems to contradict our previous findings of Experiments 3 and 4 showing no impacts of contextual support for high WM capacity individuals. However, true contradiction is only supported, if we do not accept the premise of cultural influence on our data of Experiment 5. If we accept it, we would assume perception and memory to be context-dependent in this sample to a greater extent than in a Western sample. Thus, both WM groups would also store irrelevant but context-dependent information and improvements in performance after contextual support would be a function of the amount of irrelevant information stored, and this was what we found.

Taken together, in Experiment 3 to 5 we found evidence consistent with the idea that variations in unnecessary storage costs – an indicator for optimal WM functioning –

might be reflective of variations in cognitive control abilities in general rather than selective attention mechanism per se. In Experiment 3 to 5 we observed that if cognitive flexibility and selective attention mechanisms are disentangled by allowing individuals to reconfigure the appropriate task set prior to the onset of the memory array, unnecessary storage costs for low WM capacity individuals were reduced. We could further show that cognitive control is sequentially organized and that for low WM capacity individuals the timing of selective attention mechanism seems to be a function of cognitive load. When cognitive load is high, resources for selection mechanism seem to be inefficient for early sensory mechanism (Experiment 3). By contrast, under conditions of low load, low WM capacity individuals were able to do so (Experiment 4). We further found variations in speed of cognitive flexibility to be correlated with the amount of unnecessary storage. However, due to possible cultural influences, the exact relationship between the speed of cognitive flexibility and variations in WM capacity (Experiment 5) remains uncertain. We proposed that further investigations should be undertaken to get a more elaborative understanding for this correlation.

Part 4

General Discussion

11 Interactions between Working Memory and Attention

The main focus of this dissertation project was to disentangle causes of individual variations in visual WM capacity by taking a closer look at the interplay between selective attention and WM capacity. Models of WM emphasize the concept of maintenance of relevant information, whereas models of attention focus on the encoding of relevant information in the presence of irrelevant competing information. The definitions of both constructs are therefore closely intertwined. WM and selective attention are assumed to both enhance the processing of relevant in face of competing irrelevant information (cf. Ester, Vogel, & Awh, 2013). Some theories even suggest that selective attention and WM are essentially the same. These similarities are taken into account in models of WM that posit a central role for selective attention (Cowan et al., 2005; Oberauer, 2013) and such models are supported by growing empirical evidence.

In particular, a variety of studies have shown a tight relationship between WM capacity and the ability to control attention (Conway et al., 2001; Heitz & Engle, 2007; Hutchison, 2011; Kane et al., 2001; Kane & Engle, 2003; Machizawa & Driver, 2011; Redick & Engle, 2006). Across all the different tasks used in the studies, individuals with low WM capacity were less efficient in controlling selective attention relative to their high WM capacity counterparts. In line with these studies, during the course of this thesis, we repeatedly emphasized the importance of selective attention mechanism for optimal WM functioning. We have already highlighted that attention functions as a “gatekeeper” that determines which items will be maintained in the limited WM storage (see Chapter 4.3, 8, 9, 10), indicating that only information that is attended can be stored in WM. Similarly, we assumed that reducing demands on processing resources in bilateral memory arrays can be achieved by controlling the allocation of attention onto the relevant hemifield (see Chapter 9.4). This has led to the straightforward conclusion that attention influences optimal WM functioning (see also Awh et al., 2006; Cowan, 2001; Engle et al., 1999). One aspect that is important in that regard is which subfunction of attention is necessary for gating information into WM. The general line of evidence presented in this work highlights the central role of the orienting and executive function of attention in explaining individual differences in WM capacity. While orienting describes the ability to select relevant information for privileged processing in face of competing but irrelevant sensory information, the executive attention function is assumed to resolve conflicts in information processing among competing mental processes, with low WM capacity individuals being relatively impaired in both processes (Experiments 1 to 2). In Experiments 3 to 5, we further observed that efficient gating – an indicator for optimal WM functioning – is assumed to require both processes, orienting and executive control respectively.

Important in this respect is further, that although orienting and executive attention reflect different subfunctions of attention, they are nevertheless interrelated processes. This has been shown by Jolicœur and colleagues (Jolicœur, Sessa, Dell’Acqua, & Robitaille, 2006a, 2006b). In two studies they used the N2pc – a component that is associated with selection of information for further encoding (Eimer, 1996; Luck & Hillyard, 1994). Its onset is about 200 ms post stimulus and the component is characterized by a more negative ongoing potential contralateral to the side of the target. In both studies, participants took part in an attentional blink paradigm (AB). The AB is a serial stream and involves the detection of two targets that are presented in rapid succession. Typically, accuracy in target detection is good. However, if the second target (T2) occurs within 200 to 500 ms of the first target (T1) there is a large decline in accuracy of T2. This decrement is known as AB. Some theories propose that the AB is reflective of a goal-driven process of attentional selection engaged by T1 that boosts the processing and encoding of relevant information and reduces the availability of attentional resources to detect additional targets while T1 is being still processed (Olivers & Meeter, 2008). Jolicœur et al. (2006a, 2006b) used a modified version of the AB paradigm. They presented T1 in the center of the screen but T2 was lateralized to the left or right side of the display. Accuracy of report of T2 was lower when the temporal distance between T1 and T2 was short, indicating an AB. Furthermore, and more importantly, they also found the N2pc to be reduced at short SOAs, indicating that while T1 was processed attention could not be oriented towards new information. This has been taken as evidence that orienting and executive control are mutually dependent processes. In our data, we also found evidence for interrelations between orienting and executive attention (see 14.2).

In line with the taxonomy of orienting and executive attention, we will start our discussion of "attention" effects with regard to specific processing stages that are modulated by the orienting function of attention.

11.1 Individual Variations in the Orienting Component

Orienting attention to relevant information can occur at various stages of processing tapping into an age-old debate in attention research whether selection occurs at an 'early' sensory level or 'late' postperceptual level of processing or both (Broadbent, 1958; Deutsch & Deutsch, 1963; Kahneman & Treisman, 1984; Vogel, Woodman, & Luck, 2005). According to early selection models, attention can influence processing at early sensory processing levels, prior to the full integration of different features into one object (Broadbent, 1958). Furthermore, and more importantly, it has been found that individuals can already suppress processing of distraction at this early stage (Hillyard et al., 1998; Mangun & Hillyard, 1991; Vogel & Luck, 2000). This has been taken as evidence that cognitive control can influence target selection already at early processing levels. Late selection models, by contrast, argue that all sensory information will be encoded and information is selected after different attributes are integrated into meaningful objects (Deutsch & Deutsch, 1963). Electrophysiological evidence for late selection processes was provided by Vogel et al. (1998) using the AB paradigm introduced above. For T2, they observed no evidence for ERP components reflecting suppression of sensory processing (P1/N1) or processing of semantic content (the N400 component). However, at a late stage of processing before the information enters WM (the P3 component), complete suppression was revealed, suggesting that although T2 was processed, it was never encoded into WM. It has now been established that attention operates at both stages of processing (Vogel, Woodman, et al., 2005), so that interactions between WM and attention can occur at various stages of processing and during the course of this thesis we repeatedly provided evidence for influences on both stages of processing.

In Chapter 8 we reviewed that attentional modulation at perceptual processing stages translates to subsequent memory for those objects (for a similar discussion Gazzaley, 2011). For instance, Zanto and Gazzaley (2009) found that variations in WM performance can be associated with early selection effects, with less efficient execution processes in low relative to high WM performance trials. Importantly, it could further be shown that the magnitude of such a selection process is correlated with successful WM performance (Rutman et al., 2010). Drawing upon these findings, it has been proposed that high but not low WM capacity individuals are able to suppress the influence of distraction at such an early stage of processing. However, based on the present study (Experiment 3 vs. Experiment 4) we believe that low WM capacity individuals are not necessarily slower to suppress sensory processing of irrelevant information. Instead, we argue that for low WM capacity individuals the execution of sensory item selection is dependent on the amount of cognitive load at the moment of item selection. Under conditions of high cognitive load, we observed evidence for distractor suppression at the N1 component for high but not for low WM capacity individuals (Experiment 3). After we reduced cognitive load, however, no individual differences involving WM capacity were found. High as well as low WM capacity individuals were able to inhibit the processing of irrelevant information (Experiment 4). Thus, the ability to utilize early selection processes seems to be a function of the availability of resources.

We therefore propose that individuals with high and low WM capacity might differ in the ability to allocate cognitive resources. Thus, even when cognitive load is high (Experiment 3) individuals with high WM capacity would have had sufficient resources left to suppress processing of distractors. This interpretation is supported by recent evidence showing that an individual’s estimated WM capacity score (*K*-Score, see Chapter 2) in a color change detection task varies as a function of set size. In these studies, with set sizes exceeding the estimated WM capacity, the amount of information stored in WM decreased as indexed by a drop in the estimated behavioral score as well as a reduction in CDA amplitude. However, this was only true for individuals with low WM capacity (Fukuda et al., 2015; Linke et al., 2011). Note that the slot model (see Chapter

4.1) cannot account for this finding, because it predicts that the difference between high and low WM capacity individuals should remain the same once the number of items exceeds their capacity. However, if individuals with high and low WM capacity differ in the ability to control the allocation of resources we should observe precisely the reported pattern of the findings reported by Fukuda et al. (2015). Thus, when the number of items overloads the processing resources, individuals with high WM capacity seems to be able to use their full resource potential while individuals with low WM capacity are less efficient in doing so (cf. Fukuda et al., 2015).

Differences in orienting attention to relevant target features (sensory selection) alone cannot account for variations in gating associated with WM capacity. During the processing of relevant information some conflict between relevant and irrelevant features might occur that needs to be resolved. According to models of attention, even less attended items might still be encoded if they contain relevant target features (Bundesen, 1990; Olivers & Meeter, 2008; Wolfe, 1994). In Experiments 3 to 5, distractors and targets always shared relevant attributes, namely their orientation. Thus, distractors also might still have been processed to some extent. Although the N1 component was reduced in the distractor-present condition relative to set size five in Experiment 3 and set size three in Experiment 4, it was not identical to the N1 component elicited by pure-target trials with the same number of targets, supporting the idea that the distractors were also processed to some extent. Thus, optimal WM functioning might also depend on the ability to stop the processing of irrelevant information once it has been selected. This idea taps into postperceptual stages of encoding. In Chapter 5, we have already argued that one process of particular importance to stop the processing of stimuli within the focus of attention is the ability to disengage attention. Once objects are within the focus of attention, they gain advantages in information processing (Eriksen & James, 1986) while fewer processing resources are allocated outside the focus of attention (Handy et al., 2001; Lavie, 1995). Thus, the less time attention dwells on a presented item, the lower is the probability that this item will be encoded into WM. In sum, variations in WM capacity may be reflective of differences in the ability to disengage attention form salient but irrelevant stimuli. Fukuda and Vogel (2011) tested this idea in a series of attention tasks. In their experiment 2, participants were required to report the orientation of a target Landolt C, as indicated by a preceding cue. The target stimulus always appeared together with a distractor. Shortly after the offset of the target array, task-irrelevant dots were flashed either at the target or the distractor locations (dot probe array). On the other half of the trials, no dot probe occurred. The logic behind this procedure was that electrophysiological markers should show enhanced evoked responses at locations to which attention was allocated. As electrophysiological index for attentional selection the P1/N1 complex was used, components which are assumed to be sensitive to spatial attention (Luck & Hillyard, 1994). They examined P1/N1 attention effects to the probe array, which measured the ability to resist attentional capture from distractors, and they varied the SOAs between target and probe display to test for individual variations in the time needed to disengage attention. If disengaging attention takes time and individuals with high and low WM capacity differ in disengagement speed, the electrophysiological responses to targets and distractors should not only be a function of SOA but also be related to WM capacity. They observed that at the shortest SOA (50 ms) distractors captured attention for high and low WM capacity individuals, as indexed by an equal P1/N1 amplitude elicited by dots at target or distractor locations. However, while the P1/N1 measures suggested that at the longer 100 ms SOA attention of low WM capacity individuals was still captured by distractors, the focus of attention of high WM capacity individuals was employed only onto targets. Therefore, the individual’s ability to disengage attention may be a critical trait which determines WM capacity, and it steps in when distractors have already been selected for processing. Low WM capacity individuals seem to need more time to do so, and therefore distractors might be processed and unnecessarily represented in WM, competing with relevant items for storage space.

Taken together, individual differences in the efficiency to orient attention on relevant information and to disengage attention once it has been captured seem to be an important factor when trying to explain variations in WM capacity. Apparently, the amount of cognitive resources at the moment of target selection determines at which stage of processing selective attention mechanisms for low WM capacity are efficient.

11.2 The Influence of Executive Attention

In the preceding paragraph, we argued that orienting attention can influence optimal WM functioning at a variety of processing stages. However, individual differences in focusing attention alone cannot explain the nature of individual differences in WM capacity. There has to be a central cognitive function responsible for ensuring that the dynamic control of attention is indeed goal-driven. If the number of objects that can be stored at the same time is limited, efficient utilization of limited resources becomes even more critical. During the course of this thesis we repeatedly presented evidence consistent with the idea that such a general cognitive control mechanism is the process underlying individual differences in WM capacity. For instance, we showed that WM capacity was correlated with the efficiency of resolving conflicts between competing processes or changing task demands (Experiments 1 to 4). Such variations in cognitive flexibility were measured by individual differences in the flanker compatibility effect as assessed by the executive function of attention in the ANT (Experiment 1) and variations in the speed to engage the focus of attention on relevant information (Experiments 1 and 2). Each of these tasks was based on a competition between changing task requirements. If the task changed, the old task set was required to be suppressed and the new task set to be activated. We concluded that individuals with low WM capacity were less efficient in coordinating competing processes relative to individuals with high WM capacity.

If we assume that WM encoding is a sequential process from initial sensory processing to item identification before information enters WM, the initiation of the accurate task set stands at the beginning of this causal chain. Thus, selective attention mechanisms are functionally integrated within task sets, and therefore are dependent on mechanisms of cognitive flexibility when multiple task sets need to be coordinated. As a consequence, the efficiency with which we select relevant information, and, as a result, the optimal use of limited WM resources, depends on the efficiency of cognitive flexibility. In this view, variations in cognitive flexibility account for variations in the optimal use of limited WM capacity. In Experiments 3 and 4, we tested this hypothesis (see Chapters 8 and 9). We observed that when cognitive flexibility was aided, by task set cues or single blocks, the amount of unnecessary storage cost was reduced compared to conditions with less contextual support (direction cues). Importantly, this was only the case for individuals with low WM capacity. Individuals with high WM capacity did not store irrelevant information regardless of whether cognitive control was aided or not. In order to quantify whether variations in WM capacity are not only reflective of the efficiency of cognitive flexibility, but also of the speed of this control process, Experiment 5 was conducted. Here, we systematically varied the interval between the cue display, indicating the appropriate task set, and the onset of the memory array which required the execution of selection mechanisms. With short SOAs, we found costs in WM performance in distractor-present trials, indicating that the configuration of the appropriate task set was still ongoing as the processing of targets was already required. These costs were reduced or gone with a long SOA. Although we were not able to directly link this effect to WM capacity, possibly due to cultural influences (see Chapter 10), based on our results we believe that variations in the speed of cognitive flexibility influence optimal WM functioning. However, as argued in Chapter 10, a repetition of Experiment 5 within a Western sample would bring more clarity.

Previous findings in the literature further support the idea that individual differences in WM capacity may be in part due to individual variations in the delayed initiation of selection processes. Fukuda and Vogel (2011) showed that individuals with low WM capacity are not more prone to a negative impact of irrelevant information, but that they need more time to disengage attention once it has been erroneously captured. Similarly, prolonging the exposure time for supra-capacity memory arrays systematically improves the estimated WM capacity for low WM capacity individuals compared with high WM capacity individuals (Fukuda et al., 2015). In these studies, people with low WM capacity were not less efficient in controlling attention per se, but needed more time to exert it. Based on our research, we are now able to extend these findings by highlighting the influence of individual differences in the ability to coordinate task set reconfiguration processes. High WM capacity individuals seem to be more efficient in coordinating different task set priorities. As a consequence, the initiation of specific processes which are associated with a certain task set has short delays and is highly effective. By contrast individuals with low WM capacity seem to be less efficient and/or slower in task set reconfiguration, prolonging the initiation of selection processes. If participants with low WM capacity are aided contextually to activate the task set in advance, such differences decline.

11.2.1 The Interplay Executive and Selective Attention within Working Memory

Since accurate performance in WM tasks is dependent on both selective attention and executive control, we believe that optimal use of limited WM resources is best reflected by variations in cognitive control in general rather than deficits in specific components. The question that remains is how WM theories account for the tight link between those cognitive functions. In line with the time-based resource sharing model (TBRS), we will next develop the thesis that WM functioning can be best understood by assuming that one central system is responsible for mental processes associated with processing and maintenance of information, and that this system operates sequentially so that only one process can take place at a time (Barrouillet et al., 2007).We further postulate that such a central executive function is integrated within the framework of WM.

The motivation to assume a single, central system is based on the consideration that multiple component models of WM that suggest a control mechanism that is structurally separate from WM (Baddeley & Hitch, 1974; Cowan, 1999; Engle et al., 1999; Norman & Shallice, 1986) have many drawbacks. For instance, such a system could be characterized as a homunculus (Baddeley, 1996; Miyake et al., 2000). The view of the nature of capacity limits in WM we propose here draws on single resources models that integrate an executive functioning within the framework of WM (Oberauer, 2013; Vandierendonck, 2012). Such models fractionate WM functioning into two parts. One module of WM is related to WM storage, whereas the other module involves an executive-related function. In the latter one, task set information is loaded. Since cognitive control processes are goal-driven, and thus, per definition, are functionally integrated within the task set, they are supposed to call on this executive-related function. Thus, tasks always tap into the executive function when the task set involves a specific component of cognitive control, such as selective attention. Important to note is that the modules for WM storage and executive function both suffer from limitations in the total amount of activation being available (Vandierendonck, 2012). If further both processes tap into the same resource, the allocation of limited resources to storage or executive function becomes crucial. In accordance with Carpenter and Just (1988), we suggest that variations in WM capacity in part reflect variations in the effectiveness with which limited resources are allocated to a given WM module, and high but not low WM capacity individuals would be efficient in doing so. Consequently, the optimal WM functioning for low WM capacity individuals might be achieved by telling individuals what process they should allocate resources to (Carpenter & Just, 1988).

Based on the results that we obtained in Experiments 3 and 4 (Chapters 8 and 9), we further believe that individuals with high and low WM capacity also differ in the efficiency of allocating resources within a certain WM module. For instance, when a series of varying operations that load heavily on the executive component occupy cognitive control, less time and resources are left not only for memory maintenance but also for encoding processes. If individuals with low WM capacity are generally less efficient in controlling the allocation of their limited cognitive resources, only few resources would be left for selection processes due to the sequential organization of the executive function, which in turn causes greater interference from distractors. We argued that the mixed trial structure of change detection tasks with distractors would be a suitable measure to test this idea. That is, change detection tasks with distractor-present trials require a high degree of flexibility for cognitive functioning. Individuals need to continuously switch back and forth between tasks where all items, or only a subset of items (distractor-present trials), are targets. However, because on most of the trials individuals are required to remember all items, performance costs due to task set coordination should be most evident in distractor-present trials. Important in our theoretical model is that the coordination of task requirements and selective attention both tap into the executive function of WM, but that due to the sequential organization the processing of distractors can only be stopped if the appropriate task set has been previously activated. If most cognitive resources are already consumed at the moment of item selection by task set specification, only few resources are left to stop distractor processing. Thus, the efficient allocation of processing resources seems to be important for accurate task performance. By aiding the executive functioning to select the correct task set in form of task set cues or single task blocks prior to the onset of the memory array, thereby reducing the amount of resources consumed by cognitive flexibility, we expected to improve optimal WM functioning for low WM capacity individuals. We found reduced unnecessary storage costs for low but not high WM capacity individuals in trials with contextual support relative to trials where cognitive control was less aided (Experiments 3 and 4 in Chapters 9 and 10). We further observed that for low WM capacity individuals the execution of selective attention mechanism may be related to the amount of cognitive load at the moment of target selection. If cognitive load was low, high and low WM capacity individuals were both able to selectively employ early sensory processing for target and not distractor features (Experiment 4). By contrast, if cognitive load was high, only high WM capacity individuals exhibited enhanced early sensory processing of relevant target features. We concluded that the organization within the executive function of WM is sequential and that our pattern of results is a function of a better availability of resources for low WM capacity individuals when target selection was required.

11.3 Attention to Internal Locations within Working Memory

Besides selective influences of attention before memory encoding, it has likewise been shown that attention can also be oriented to stimuli that are already maintained in WM (Awh, Dhaliwal, Christensen, & Matsukura, 2001; Downing, 2000; Duncan, 1984; Griffin & Nobre, 2003; Matsukura, Luck, & Vecera, 2007; Theeuwes, Kramer, & Irwin, 2011; Van Moorselaar, Gunseli, Theeuwes, & Olivers, 2015). For instance, Griffin and Nobre (2003) found a significant cueing effect for cues that were presented with a time delay of 1.5-2.5 sec after the offset of the memory array in a color change detection task. In Experiment 2 from Griffin and Nobre (2003), participants were presented a memory array consisting of four colored Xs. After a delay period one test item appeared and participants responded to whether the color of the test item and the item presented at the corresponding location in the memory array matched. Importantly, informative pre-cues (before the presentation of the memory array) or retro-cues (after the offset of the memory array) indicated the location that would be probed with 80% validity. As a baseline, neutral trials (non-cued) were included. Compared to neutral trials, participants performed faster and more accurately on valid and even slower and less accurately on invalid trials. This pattern of results was equivalent for pre-cues and retro-cues. Thus, cueing an item during the delay period resulted in better WM performance compared to when an item was not cued indicating that attention can influence and enhance item representations that are already being maintained in WM.

According to Matsukura et al. (2007), the beneficial effect of cues after the offset of the memory array is due to a protective selective attention mechanism. Since the cue is displayed after stimulus offset, no prioritization of perceptual processing can be accomplished. Selective attention mechanisms are assumed to protect the mnemonic representations against passive decay or inter-item interference. Van Moorselaar et al. (2015) further evaluated the dynamics of setting up this protection mechanism by systematically varying the time interval between cue onset and a visual mask in a memory task in a series of experiments. Recall performance was better on cue trials with and without a mask, suggesting that protection already operates during maintenance. Importantly, Van Moorselaar et al. (2015) showed that the protection mechanism is fully established at around 600 ms following the cue. Here, no interference effects on WM have been reported any longer. Further evidence, that setting up selective protection mechanisms requires time, has been observed by Pertzov, Bays, Joseph, and Husain

(2013). They used variable delays between retro-cues and memory probes and found significant effects of cues on WM performance if the delay was at least 300 ms. Together, the reviewed evidence suggest that attention towards internal representations can counteract effects of interference or decay. However, this protection mechanism takes time.

11.4 Attention-based Rehearsal in Working Memory

In the last section, we reviewed evidence that selective attention appears to affect information already stored in WM. Now, we focus on the cognitive mechanism by which this protection mechanism is achieved.

Spatial attention plays an important role in many WM theories. Maintenance of information is assumed to be achieved via sustained allocation of attention towards mnemonic representations (Awh & Jonides, 2001; Postle, 2006; Zimmer, 2008). A large part of the theoretical underpinning of this idea was based on work of Smyth and Scholey (1994) suggesting that WM maintenance in the Corsi task (see Chapter 2.1) involves shifts of spatial attention. In Experiment 4, we also argued that enhancing the processing of a limited number of objects would be accomplished by attention on relevant items. In Chapter 4.3, we further emphasized that attended information gets a competitive advantage in contrast to unattended information (Duncan, 1981). These processing improvements might begin at early sensory levels and “[..] operate in the service of memory as well as perception, by providing a functional marker for location-specific representations in WM” (Awh & Jonides, 2001, p. 119). This idea was, for example, put forward by Awh and Jonides (2001), who affirm that sustained allocation of attention is a rehearsal mechanism for WM storage. Their theory is based on research showing typical effects of spatial attention such as improving visual processing efficiency for stored objects in WM (Awh et al., 1999; Awh, Jonides, & Reuter-Lorenz, 1998). First, a clear overlap in brain regions elicited by spatial attention and memory processes were found (Awh, Smith, & Jonides, 1995). In order to learn more about the timing and spatial topography of spatial attention to memorized information, Awh, Anllo-Vento and Hillyard (2000) conducted a spatial WM task in which during the retention interval irrelevant probes were flashed either at the-to-be memorized location or at a different location. They observed that early ERP components were enhanced to probes appearing at the same location as the mnemonic representation and were similar to those after an attention task using identical stimuli with no need to maintain those stimuli. Thirdly, such modulations of early sensory processing is elicited at visual areas contralateral to the attended locations beginning at about 100 ms after stimulus onset (e.g. Gratton, 1997), suggesting changes in processing efficiency at memorized locations . Fourthly, Awh et al. (1998) found that choice stimuli were responded to faster if they appeared at the same position that was currently stored in WM, indicating that attention was oriented towards this location. As main tasks participants were required to remember the location (see their experiment 1) or identity of a stimulus (see their experiment 2). During the retention interval a probe appeared either at the same or a different position and participants were required to press a button as fast as possible as soon as this probe stimulus appeared. In the spatial condition, participants responded faster to probes appearing at locations held in WM relative to irrelevant locations. However, no or little facilitation effects were found if the memory task was nonspatial (experiment 2). Finally, their experiment 3, Awh et al. (1998) showed that WM maintenance is impaired when an intervening task interrupted the allocation of attention to memorized locations. Participants were engaged in a spatial memory task in which they had to retain single locations. Crucially, a second color-discrimination task was interleaved during the retention interval of the memory task. There were two conditions of the color-discrimination task. In one condition, the-to-be classified stimulus appeared at any position of the screen, and therefore required a shift of attention away from the memorized stimuli. In another condition, however, the presented color stimulus was large enough to include all potential memorized locations, and therefore the focus of attention could remain on the memorized location. WM performance was better, if no spatial shifts were required. Taken together, the evidence suggests that the maintenance of information is indeed achieved via sustained allocation of attention towards mnemonic representations.

11.4.1 Does Attention-based Rehearsal Influences Performance in Change Detection Tasks?

The need for participants to remember specific positions of objects in change detection tasks is often overlooked. For instance, in our version of the change detection task (e.g. Chapter 8) participants are instructed to report the orientation of only one object maintained in WM memory. Specifically, they were asked to judge whether the memorized object corresponding to the location of the test item has changed or not. Thus, optimal WM performance depends crucially on the comparison process of the item features of the probed location with the remembered item features corresponding to a specific position. If this identification process is incorrect and the orientation of one of the non-probed items (i.e. those in different spatial locations) is retrieved, errors are more likely to occur emphasizing the role of memory for location for performance (see Bays, Catalao, & Husain, 2009 for a similiar discussion).

This role has further been demonstrated by implementing a dot probe reaction time task within a visual memory task (Downing, 2000; Theeuwes et al., 2011). In one particular study conducted by Theeuwes et al. (2011) participants were required to maintain four colored squares. Memory was tested by asking participants whether a specific color was among the remembered objects, for example by the probe “red?”. After receiving this question, they were required to determine whether the color red was present in the array or not by making a simple yes or no answer. Critically, on some trials, a white probe appeared after the offset of the question “red?”. It was presented at one of the four locations with a certain probability that the probe dot location coincided with the location of the tested memory object. Participants were asked to give a speeded response to the probe. The results revealed faster reaction times to the probe when the location of the probe was identical with the position of the ‘retrieved’ memory item. These results converge with previous findings showing that WM performance is less accurate when the contextual information at the test array is different to the memory array (Jiang et al., 2000) or the spatial configuration has changed (Zimmer & Lehnert, 2006), even when these features are completely irrelevant or when the names of the shapes rather than the actual shapes were displayed at the test array. Taken together, the results promote the idea that object identities are naturally integrated within spatial positions in WM.

Interestingly, previous theoretical accounts confirm a central role of spatial attention for feature integration (see for a review Treisman et al., 1993). Remembering various objects with several features imposes a load on the system that is employed in order not to confound the different features at the moment of retrieval. One way to overcome this problem and avoid confusion would be to integrate the features in object files. According to Treisman and Zhang (2006) spatial attention plays an important role in doing so. Each object feature will be assigned to a specific position, and features belonging to the same position are bound into object files. Consequently, integrated object features are more vulnerable to location changes than single features. If the spatial configuration is changed, the identification process of the corresponding memory array is disrupted, resulting in a mismatch between the presented and the remembered information (Bays et al., 2009; Jiang et al., 2000; Zimmer & Lehnert, 2006).

We propose that the recruitment of spatial attention in the service of a rehearsal-based protection mechanism, as described in the preceding paragraph, is therefore also involved when performing change detection tasks. This is not trivial, especially because WM seems to encode the spatial properties of the stimuli it represents and combine it with perceptual information into one object file (e.g. Treisman & Zhang, 2006; Zimmer, 2008). Thus, allocating spatial information to objects might play a special role in WM performance as assessed in change detection tasks, because participants need to remember locations of the memory items as long with their perceptual features as color, shape or orientation, even if they are not required to report changes in location. That is, in order to report changes in object features between the test array and the items held in memory, participants must determine a judgement for each memory item based on the comparison between the probe items' locations and the retained locations of each memory item (Bays et al., 2009). Thus, subjects must have allocated their attention to the location of the memory items and applied a rehearsal-based attention mechanism for memory maintenance of both spatial and perceptual information. Now, we will discuss which role the CDA might play in this particular process.

11.4.2 The Role of the CDA

In Chapter 3 of this thesis we introduced the CDA as a valuable electrophysiological correlate for WM maintenance (e.g. McCollough et al., 2007; Vogel & Machizawa, 2004). Its amplitude has not merely been shown to be sensitive to the amount of information being stored and individual differences in WM capacity (Vogel & Machizawa, 2004) but also seems to be a powerful tool to examine how attention control directs the encoding of information into WM (McCollough et al., 2007; Vogel, McCollough, et al., 2005). Based on these characteristics, we thought of CDA amplitude as a well suited electrophysiological reflection of WM functioning for our intended investigations.

However, in Experiments 3 and 4 we showed a clear discrepancy between behavioral performance and WM correlates. Although behavioral performance in distractor-present trials was clearly improved in trials where cognitive control was aided (task set cue, single block) relative to trials with less support (direction cues), CDA amplitudes in trials where cognitive control was aided was just as large as CDA amplitudes to sole direction cues. This discrepancy was unexpected based on the idea that both performance and CDA amplitude reflect WM maintenance. Of course it might be the case that the behavioral improvement in WM performance after task set reactivation was not due to better control of item selection producing less unnecessary storage of irrelevant items, but a result of a more precise representation of the selected items. However, for reasons explained in Chapter 9.4, we consider a resolution of WM representation an unlikely explanation of our behavioral findings. Instead, we postulate that the CDA is not a direct correlate or ’signature’ of memory storage (cf. Postle, 2015) but a relative measure of the focusing and distribution of attention across objects which is related to but not identical to the number of stored items.

The motivation to assume the CDA to be related to the efficiency of allocating attention is based on a growing amount of evidence. For instance, it has been shown that CDA amplitude in change detection trials is identical for objects that remain on the screen until memory is tested to those measured for stimuli that are no longer visible (Tsubomi, Fukuda, Watanabe, & Vogel, 2013). Awh, Anllo-Vento and Hillyard (2000) have further shown that sustained spatial attention towards the locations of the remembered objects influences maintenance of items in a spatial WM task. Thus, it is very plausible that CDA amplitude is sensitive to spatial properties of memory items. The organization of the visual system as well as the CDA are both contralateral in nature, further supporting this idea. Additionally, the CDA is in part generated in cortical areas that are at least partly associated with topographic mappings of location (McCollough et al., 2007).

Although these patterns suggest that the CDA is associated with spatial attention, as described in Chapter 3.1 there is also evidence that the CDA could be dissociated from the number of locations that are relevant for the task (Ikkai et al., 2010), which is in apparent contrast to this idea. However, these results do not lead to the straightforward conclusion that CDA amplitude is indeed modulated by the number of objects. As argued in the preceding chapter most objects are compounds of multiple attributes and it is possible that individuals do not store complete object but single features. For instance, Woodman and Vogel (2008) evaluated whether CDA amplitude is sensitive to item content. In their study, participants underwent a bilateral change detection ask with multifeature objects. Despite identical physical conditions between the color and orientation conditions, they observed larger CDA amplitudes for the latter condition. A critical aspect of their results was that the increase in amplitude for orientation and the number of items presented did not interact. Thus, the increase in amplitude from set size two to four items was identical for color and orientation indicating that the CDA reflects item content at least some extent (Perez & Vogel, 2011). However, what types of features are represented is still undetermined. Future research across a much broader range of different types of objects will be necessary to characterize the exact nature of CDA amplitude better. Nevertheless, we believe that one important feature that affects CDA amplitude in change detection task is item location.

As we have discussed in the preceding Chapters (see Chapters 11.4 and 11.4.1) spatial attention also plays an important role during WM maintenance for complex objects. When attention is withdrawn, objects might fall apart into their various features (Wheeler & Treisman, 2002). This converges with Awh’s interpretation that spatial attention functions as a rehearsal mechanism to maintain information in an active state in WM (Awh & Jonides, 2001). We reason that the CDA is reflective of this rehearsal-like function of spatial attention over the delay period. It is assumed to code the integration of different features into an object file via sustained attention to their specific position. From this view, the integration of complex information should result in larger CDA amplitudes. Supporting evidence for this notion has been revealed by Woodman and Vogel (2008) who observed different CDA amplitudes as a function of the object feature being maintained. Further evidence that CDA amplitude might also encode spatial information was observed in multiple object tracking (MOT) tasks. In such tasks, individuals are required to track several marked objects on the screen. All other objects are irrelevant and should not be tracked. When the objects stop moving, participants have to indicate all the tracked objects. In such tasks, a similar CDA was found as in visual change detection tasks. Thus, adequate task performance requires selecting and sustaining the spatial location of the targets and the CDA seems to be reflective of this. With increasing number of targets being tracked, the amplitude of the CDA increased (Drew, Horowitz, & Vogel, 2013; Drew, Horowitz, Wolfe, & Vogel, 2011; Drew & Vogel, 2008). Additionally, it has been shown that tracking the changing positions in MOT task produces larger CDA amplitudes than those extracted from a color change detection task (Drew et al., 2011). Thus, CDA amplitude might be a relative measure of the focusing and distribution of attention across objects. This process is related to the maintenance of objects but not identical with it.

However, this interpretation of CDA amplitude requires further research. One way of further investigating this might be to apply a study design that allows to further disentangle visual and spatial information. For instance, one might think of a similar change detection task as applied by Ikkai et al. (2010, see Chapter 3.1), but with different stimulus material. Instead of remembering color features, individuals could be asked to retain the orientation of stimuli or even maintain sounds. Specifically, four different sound could be serially displayed at different locations. However, two of the stimuli would always be displayed at the same location. Such a study design would allow distinguishing whether the CDA is reflective of the number of stimuli or the number of remembered locations.

Instead of being constrained to measuring the CDA, one might think of the utility of slow waves (without applying the contralateral subtraction technique) as electrophysiological correlate of WM storage. In the next chapter we take a closer look at the slow potentials from which the CDA as a difference wave is calculated.

12 Reconsidering Slow Potentials

An alternative approach to using CDA to evaluate WM functioning is the more direct investigation of slow potentials. The amplitude of posterior contralateral slow potentials has already in prior studies been shown to be reflective of WM maintenance (Arend & Zimmer, 2011; Liesefeld et al., 2014; Robitaille & Jolicoeur, 2006; Vogel & Machizawa, 2004). However, as detailed in Chapter 2.4, one challenge for the interpretation of slow potentials is that numerous non-mnemonic processes (such as effort, arousal, task difficulty, etc.) may be reflected in their amplitude. These task-general processes may partly be responsible for larger amplitudes with increasing set size. Fortunately, Vogel and Machizawa (2004) have shown that such task-general processes do not affect lateralized slow potentials.

Recently, the utility of slow potentials over CDA amplitude in understanding the nature of WM functioning have repeatedly been discussed in the literature. For instance, Arend and Zimmer (2012) found that the pattern of contralateral slow potentials better paralleled their behavioral accuracy data than the CDA pattern. Specifically, they found effects of maintenance as well as effects of item selection in both contralateral slow potential and accuracy patterns but not in the CDA pattern. They argued that contralateral slow potentials reflect other processes related to optimal WM functioning than CDA amplitude. However, further investigation is necessary to better understand the underlying causes of this dissociation.

One way of studying this is to take a closer look at ipsilateral potentials since the ipsilateral activity is used to control for unspecific contralateral activity when quantifying CDA amplitude (see Chapter 2.4). Interestingly, recent research also revealed a load-depending modulation of ipsilateral potentials (Robitaille, Grimault, & Jolicœur, 2009). Theses amplitude modulations are exclusively caused by the processing of irrelevant items and are more likely when the number of irrelevant stimuli is small (Arend & Zimmer, 2011). More importantly, it has been shown that the influences of the number of items on ipsilateral slow potentials are related to variations in WM capacity, with load dependent influences being present only for low WM capacity individuals (Fukuda et al., 2015). These results suggest that the allocation of attention towards the relevant hemifield and away from the irrelevant one is an important mechanism to ensure optimal WM functioning. The more processing resources are available for relevant objects, the more likely is their encoding into WM (Bundesen et al., 2005; Bundesen, 1990). The effectiveness of this process is influenced by selective attention (Hillyard et al., 1998), as we also showed in Experiment 4 (see Chapter 9). Here, we found reduced amplitudes at the ipsilateral hemisphere when the execution of reconfiguration processes was aided, with a larger reduction for individuals with low WM capacity. As reviewed above, if individuals are better in allocating attention on the relevant hemifield, fewer resources will be consumed for the processing of irrelevant information.

Taken together, the utility of slow potentials in investigating WM processing has several benefits. First, contralateral slow potentials are not merely sensitive to the amount of information being stored but they do also reflect selection mechanisms relevant for optimal WM functioning. Second, by comparing activity patterns at ipsilateral and contralateral hemispheres we can learn more about differences in WM capacity associated with the ability to allocate attention on objects. Further investigations should be undertaken to get a more elaborative understanding of slow potentials.

13 Conclusion

We have argued that individual differences in WM capacity are best understood by considering interactions between attention and WM. We found that a broad class of cognitive control processes contributes to this interaction. In the first part two experiments focused on a specific selective attention mechanism, namely the ability to allocate attention towards targets. We found that this process is more efficient and faster in individuals with high WM relative to low WM capacity individuals. We further showed that the magnitude of costs associated with deficits in voluntarily allocating attention is related to the ability to reconfigure the appropriate task set. Such reconfiguration processes take time and individuals with high and low WM capacity differ in speed of doing so, with low WM capacity individuals being slower. If the task set always remained the same, no individual variations associated with WM capacity were found. Thus, the ability to flexibly switch between changing task demands seems to be crucial for optimal WM functioning and individuals with high and low WM capacity differ in efficiency and speed of this process.

In the following part of this thesis we further developed this idea by investigating individual differences in unnecessary storage costs that have been previously associated with differences in WM capacity. In a series of three experiments we observed that unnecessary storage costs in low WM capacity individuals are reduced if the initiation of the appropriate task set was aided. This was achieved by a priori task set cues or single distractor-present blocks with no need for task set reconfiguration processes. The magnitude of this improvement was associated with the amount of available cognitive resources. We even went one step further and argued that the ability to utilize early selection processes is to be related to the total cognitive load at the moment when the selection process is executed. When the amount of cognitive load was reduced, individuals with low WM capacity were as efficient as high WM capacity individuals to ensure that only relevant items enter WM. On an electrophysiological level, this effect was reflected by early sensory suppression of irrelevant information. We reason that the same attentional processes are recruited for the active maintenance of information within WM as for visuo-spatial selection and that the CDA reflects this process. However, there are still some unresolved issues in this hypothesis that need to be resolved. We outlined one possible design for future research in order to do so.

In sum, we were able to show a tight relationship between attention and working memory, which is associated with a broad class of cognitive processes, reflecting the diverse modes of operation within each of these systems. The amount of consumed processing resources and the ability to resolve conflict between competing processes seem to be important characteristics in this multifaceted relationship.

14 Appendix

Table 14.1. *Mean amplitude for ipsilateral and contralateral slow waves in a time window between 800 and 1000 ms for low WM capacity individuals from Experiment 3.*

	Set Size		
Hemisphere	2T	2T3D	5T
Low WMC			
Ipsilateral	-1.18 (.80)	-1.36 (1.02)	-1.13 (.91)
Contralateral	-1.73 (.75)	-2.27 (1.10)	-1.73 (.95)

Table 14.2. *Intercorrelations between three functions of attention from the ANT of Experiment 1.*

	Alerting	Orienting	Executive Control
Alerting	1	-.05	.12
Orienting	-.05	1	.23+
Executive Control	.12	.23+	1

Note. + *p* < .08

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