Limitations in Dual-Task Performance

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Aan mijn ouders

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List of Abbreviations

AB	attentional blink
AEC	adaptive executive control
ANOVA	analysis of variance
CCW	counter clockwise
CW	clockwise
ECTVA	executive control theory of visual attention
EEG	electro-encephalogram
EOG	electro-oculogram
ERP	event-related potential
fMRI	functional magnetic resonance imaging
HEOG	horizontal electro-oculogram
IQ	intelligence quotient
LRP	lateralized readiness potential
MEG	magneto-encephalogram
MSE	mean square error
N2pc	negative 2 posterior contralateral
OSPAN	operation span
PC	percentage correct
R	response
RSVP	rapid serial visual presentation
RT	reaction time
PRP	psychological refractory period
S	stimulus
SD	standard deviation
SOA	stimulus onset asynchrony
SPCN	sustained posterior contralateral negativity
SPM	standard progressive matrices
SEM	standard error of the mean
T	task
TEC	theory of event coding
TVA	theory of visual attention
VEOG	vertical electro-oculogram
VSTM	visual short-term memory
WM	working memory

Chapter 1

General Introduction

Working memory is the active part of the brain that is occupied with short-term maintenance and active processing of information. If information such as stimuli and goals is task relevant, it is activated in working memory. Processes such as retrieving, manipulating or combining information also use working memory. Working memory is capacity limited, something that is revealed when working memory is increasingly taxed, for example when you have to remember a large list of groceries, or when you have to perform more tasks at the same time. Therefore, to study working memory and its limitations, it makes sense to increase the information burden of working memory systematically, and to investigate performance impairments. In this thesis, this is accomplished by presenting two tasks instead of one in a variety of dual-task paradigms.

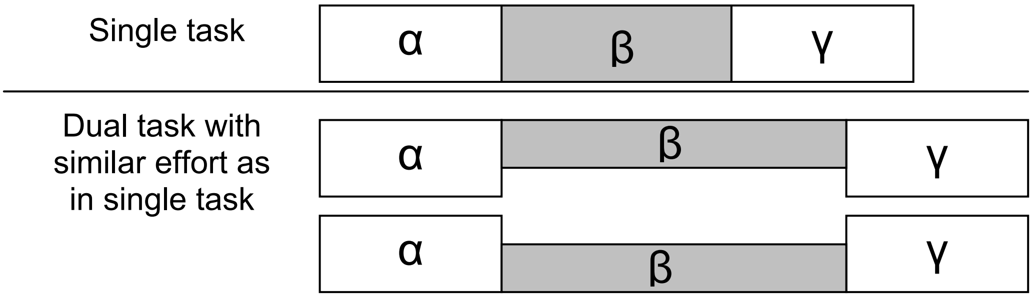

Figure 1.1. Conducting the two tasks from a dual task takes longer than conducting a single task. This is caused by a capacity-limited process (block β; in grey), while processes before and after this capacity-limited process (blocks α & γ; in white) are not affected. The lower panel illustrates a model in which two competing processes share the available capacity (e.g., Tombu & Jolicœur, 2003).

Dual tasking, or doing two things simultaneously, is something we engage in our daily lives, for example when we drive a car and talk on our handsfree phone at the same time. When driving on an empty motorway, talking on the phone is relatively easy to do, but talking on the phone while crossing a large, busy roundabout is more difficult. In the end, the easiest way to talk to someone on the phone remains when you are at home, sitting on the settee. Responding to one task is always faster than when you combine that same task with another task (e.g., Bertelson, 1967; Gottsdanker, Broadbent, & Van Sant, 1963) as a consequence of the limited capacity of working memory (see Figure 1.1). The response delay that arises by doing two tasks instead of one depends on the circumstances. The size of that delay is determined not only by task difficulty but also by the combination of task properties (e.g., Hommel, 1998;

Logan & Schulkind, 2000). The available research does not explain what exactly these limitations are, how they come about and what they are dependent on. This thesis is aimed to rectify this situation.

In this introduction, first a brief history and several important dual-task paradigms are described. Then, the different subprocesses involved in dual-task processing are explained to a wider extent, together with the meaning of attention in general and for dual-task processing specifically. Subsequently, an introduction in electrophysiological processing is presented; a method that is used in a later chapter. With this information, the occurring delays in dual-task processing are explained, as are the most important models that are used to describe results from dual-task experiments. Then, two specific classes of limitations are set out: structural and functional limitations. They are part of different models and they both predict different outcomes in situations that will be investigated later in the empirical section of this paper. Lastly, the thesis question and the outline of the thesis will introduce and structure the chapters that follow.

Early dual-task studies

In the early dual-task literature, research focused on discerning the amount of impairment between different task combinations, similar to measuring the delay that occurs when you use your mobile phone and drive your usual car compared to when you use your mobile phone and you drive a van with a trailer. In the latter case that will be harder to combine. Fitts (1954) conducted several dual tasks in which two closely related motor tasks were combined. Results showed a decrease in performance speed that suggested that combining two closely related motor tasks was capacity limited. Fitts (1954) concluded that this decrement was caused by a limitation in the monitoring process of these movements (see also: Michon, 1964; 1966). Likewise, Posner and Rossman (1965) showed decreasing performance on a memory task with increasing difficulty of the additional mental task. These data were confirmed by Norman and Bobrow (1975) who described a general model for the limitation of dual-task processing. They assumed that there is a fixed amount of resources that can be used, and dual-task processing is delayed when more resources are required than there are available (see also: Kahneman, 1973; Navon & Gopher, 1979). Subsequently, the focus shifted from a more capacity oriented approach to a more task-combination oriented approach. For example, research investigated whether the combination of task modalities (e.g., auditory modality, visual modality, etc) influenced dual-task performance. Driving a car and talking on the phone is easier than driving a car and looking at the map to see where you need to go (for obvious reasons). Baddeley and Hitch (1974) proposed a working-memory model in which they distinguished a visual-spatial storage modality, an auditory storage modality, and a central executive that controls the operations on the stored information. Applying the model to dual tasks, it can be argued that performance on dual tasks restricted to one modality, the visual, say, suffers more than performance on dual tasks presented in two different modalities, the auditory and the visual, say (see also Brooks, 1967, 1968). Later, interest arose into the effect of cross-talk between tasks (e.g., Navon & Miller, 2002). During cross-talk, properties of one stimulus can influence the response to the other stimulus when they are presented at the same time in the same visual field. Navon and Miller (2002) suggested that when two tasks overlap, the available resources can be divided among the two tasks, although the first task (T1) will have priority. Because both tasks – and particularly the capacity-limited processes of the tasks - can be active at the same time, cross-talk can occur and properties of the second task (T2) can influence the reaction time for the first task (RT1). T1 properties can always influence the reaction time for the second task (RT2), even without cross-talk, for example when T2 is a repetition of T1.

Dual-task paradigms

There are multiple dual-task paradigms that show the limitations that we experience when we do two things at the same time, for example the dichotic listening paradigm (Broadbent, 1958), the task switch paradigm (Jersild, 1927; Rogers & Monsell, 1995), the Psychological Refractory Period (PRP) paradigm (Telford, 1931) and the Attentional Blink (AB) paradigm (Raymond, Shapiro, & Arnell, 1992). The latter two will be used in the current thesis. In all four paradigms, working memory is overloaded, which makes it possible to measure the boundaries of working memory. Additionally, in the dichotic listening paradigm and the attentional blink paradigm attention plays a significant role.

In the PRP paradigm two stimuli – stimulus 1 (S1) and stimulus 2 (S2) - are presented shortly after each other (see Figure 1.2A). The time between S1 presentation and S2 presentation is called the Stimulus Onset Asynchrony (SOA), which typically varies within a range of 50 ms to 1000 ms. Response to S1 and S2 (R1 and R2) is speeded. At short SOAs there is more task overlap and the reaction time to RT2 is longer compared to RT2 at longer SOAs (when there is less task overlap; Welford, 1952). This is expected considering that a large SOA more closely resembles a single task, especially when the response to the RT1 has already been given. The response to both the stimuli is still slower than when the tasks would have been performed in a single-task setting (Jentzsch, Leuthold, & Ulrich, 2007).

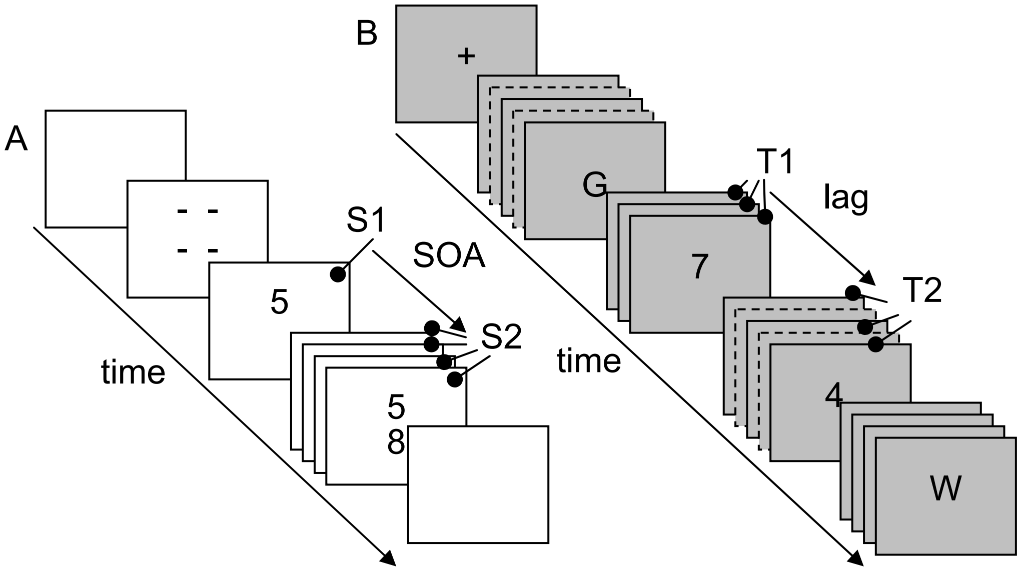

Figure 1.2. (A) An example of a PRP trial. After the fixation that indicates the boundaries in which the stimuli are presented, S1 is presented and after a delay – the SOA – S2 is also presented on the screen. Responses for both stimuli are speeded. (B) An example of an AB trial. After a fixation that is used to centre people's attention, a rapid stream of letters is presented. Within the stream, two digits are presented that serve as targets. The distance (lag) between the two digits can vary. Unspeeded responses are required at the end of the trial.

In a typical AB paradigm, a series of characters is presented one after the other in the centre of the screen in rapid succession (see Figure 1.2B). Two targets are placed within that series with a variable number of distractors in between them. The two target stimuli require unspeeded responses at the end of each trial. The accuracy of reporting Target 1 is generally high, whereas the accuracy of reporting Target 2 depends on the place it takes after Target 1 (i.e. the lag) and the number of targets separating them usually varies from zero (lag 1) up to 8 (lag 9). Long lags show good Target-2 performance while lags up to 500 ms show impaired Target-2 performance (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). This impairment is called the attentional blink and it is considered to express an inability to process Target 2 up to a conscious level when Target-1 processes have not yet been completed (Sergent, Baillet, & Dehaene, 2005; Vogel, Luck, & Shapiro, 1998). Both the PRP paradigm and the AB paradigm investigate dual-task interference. The former investigates interference that is created when two tasks are presented simultaneously and the latter investigates interference as after-effect of Target 1 processing. The two paradigms are often attended to separately, although occasionally they are treated together (e.g., Jolicœur, 1999). Jolicœur and Dell'Acqua (1999) suggest that the AB magnitude and the PRP effect are based on similar mechanisms (see also Jolicœur, 1999), an idea that was further investigated in this thesis. Additionally the PRP effect and AB magnitudes were compared with a variety of constructs like working memory and IQ that might explain their similarity. Working memory and IQ were both measured because they are related but they are not the same (Conway, Kane, & Engle, 2003; Süβ, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). If participants would make use of working memory when they execute the PRP paradigm as well as when they execute the AB paradigm, then increased working memory costs would have an effect on AB and PRP performance although research shows that this effect is not as straightforward (e.g., Akyürek, Hommel, & Jolicœur, 2007).

Jolicœur and Dell'Acqua (1999) investigated memory encoding in a dual task and proposed a two-step mechanism on how information is encoded into memory. Information is transported via sensory encoding to a more sustainable perceptual encoding stage. During sensory encoding, the to-be-encoded information can be overwritten by other sensory input, for example by masking. When the information has reached the perceptual-encoding process stage, masking can no longer overwrite the information, but the information in here needs to be consolidated or it will decay. As soon as the information is consolidated, it becomes conscious and will be stored in memory. In two dual-task experiments, Jolicœur and Dell'Acqua (1999) showed that short-term consolidation of a character in an identification task postponed response selection of a tone-distinction task independent of which task was presented first. This demonstrated that memory encoding is capacity-limited just as response selection.

The AB is particularly useful to study short-term consolidation and delay, because of the speed of the rapid presentation of visual stimuli that all mask each other, including the two targets that need unspeeded response at the end of each trial. Chun and Potter (1995) suggested that the blink occurs because short-term consolidation of the first target defers short-term consolidation of the second target. As a consequence of the mask presented immediately after the second target, Target 2 will decay and accordingly will fail to reach visual short-term memory.

In this thesis, the PRP paradigm is mainly used because the concurrent presentation of two stimuli creates an ideal opportunity to investigate dual-task interference. The PRP paradigm shows that performing multiple tasks is not possible without costs. These costs are expressed in longer reaction times or lower accuracy on the tasks. The costs can occur when priming T1 properties (e.g., features) influence the performance on the secondary task (T2), or vice versa. Consider a task in which people need to respond with their right hand to a red circle and with their left hand to a green circle. They will tend to respond quicker to a red circle if it was preceded by another red circle than if it was preceded by a green circle. This repetition effect is called priming. If R2 is a repetition of R1, then RT2 is quicker than if R2 is different from R1. Vice versa, T2 properties can influence T1 performance only when T2 properties are already activated before the T1 response decision has been made. In our example, this situation would translate to a facilitation of R1 if this was followed by a similar color compared to if it was followed by a different color. Since this effect works in opposing direction (from T2 to T1) and it describes compatibility for features or processes (e.g., color), this effect is called the backward-compatibility effect (which depends on cross-talk). The backward-compatibility effect gives us information on what T2 processes are available before T1 response decision and is therefore a very useful tool to study in what way two tasks can be performed concurrently, and which processes are limiting this concurrent processing.

Subdivision of processes

Figure 1.3. A discrete serial three-stage model (cf. Sternberg, 1969)

As described in the first part, it is the overlap of processes between the two tasks that causes dual-task slowing. In order to study this, performance on these tasks can be subdivided into different processes and subprocesses. This makes it easier to distinguish which (part of the) process causes the slowing. Sternberg (1969) proposed discrete serial models such as a three-stage model (see Figure 1.3) in which several subprocesses are differentiated from stimulus onset to when the response is executed. When a stimulus is presented, first early, perceptual processes (e.g., color) are performed, ending with the classification of the stimulus. Next, response selection is initiated, which constitute the capacity-limited part of processing (see e.g., Pashler & Johnston, 1989). After the response has been selected, response execution can commence. Adapting this model for dual tasks made it possible to distinguish which processes are operated in what order and how they overlap. Although there is evidence that stages are not discrete and serial, but rather continuous and overlapping (e.g. Miller & Hackley, 1992), serial stage models have proven to be useful in investigating sources of dual-task interference. Drawbacks of the model are that in reality, the distinction between the different subprocesses is not so clear-cut, and in more complicated tasks more subprocesses are involved.

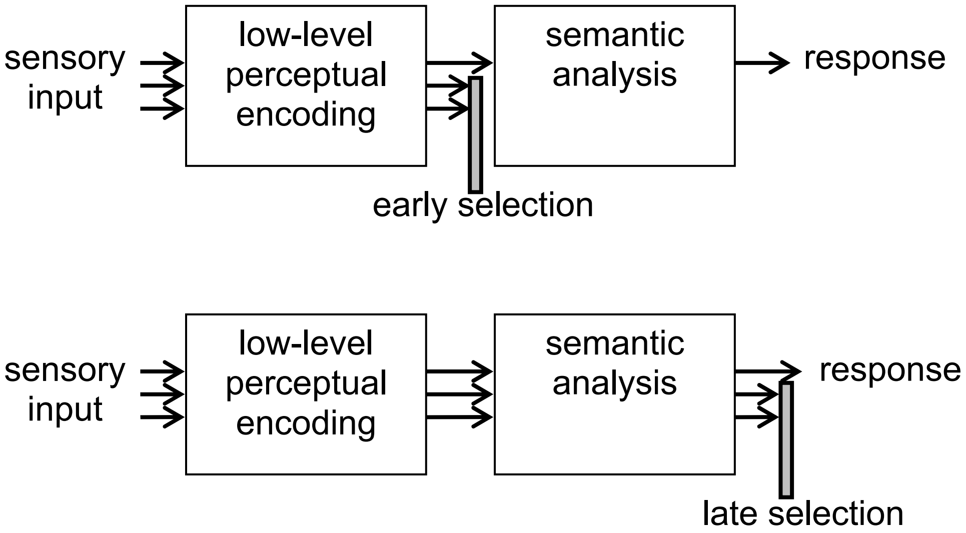

Figure 1.4. Schematic presentation of the early vs. late selection models of attention

Attention selects relevant information, and it monitors what we store in our memory. Two main models have been put forward that describe the way attention operates: the early-selection model (Broadbent, 1958) and the late-selection model (Deutsch & Deutsch, 1963) (see Figure 1.4). In the early selection model (Broadbent, 1958), information is encoded up to perceptual encoding, but no meaning is added; instead, information is encoded according to physical characteristics. In the late selection model, all information is processed beyond perceptual encoding, up to the level of semantic analysis. At the late selection point it is decided which information is entered into memory to be identified (Deutsch & Deutsch, 1963). Because of the decay that occurs after short-term consolidation (see Jolicœur and Dell'Acqua, 1999) information that is not selected into memory will decay (i.e. will be forgotten).

Both attentional models show that there are limitations to our capacity to process information. As described earlier, dual-task processing is also vulnerable to capacity-limited processing. It is currently unclear to what extent these attentional limitations are caused by the same mechanism as dual-task limitations (e.g., Brisson & Jolicœur, 2007a; 2007b; Johnston, McCann, & Remington, 1995; Pashler, 1991). Therefore it is necessary to investigate the role of attention in dual-task processing, and how it relates to the limited-capacity processes responsible for dual-task interference. In this thesis, the effect of visual-spatial attention was measured in a dual task. Visual-spatial attention is used to locate information at a specific position on a visual screen. If attention occupies the same limited-capacity process that is also responsible for dual-task interference, attention should be delayed by competing processes.

Event-related potential (ERP)-measurements in dual-task processing

Electrophysiological measurements can be used as a tool to distinguish different processes and to study whether they can overlap or delay each other. Some electrophysiological measurements are markers for the timing of different subprocesses. Any electrophysiological activity related to a particular event is called an event-related potential, or ERP. The so-called “P3” is an example of an ERP component that is represented as a peak-amplitude on a waveform. Factor-related modulations of the P3 are thought to reflect target processing up to a level of consciousness (Donchin, 1981; Nieuwenhuis, Aston-Jones, & Cohen, 2005) and are only sensitive to the duration of processes preceding response selection. In the AB paradigm, the P3 is only seen when the target has received the correct response. When an incorrect response is given by the participant, the waveform doesn’t show a P3 (see Figure 1.5). This modulation of P3 shows that only when information is processed up to a conscious level, participants are able to report the second target. Furthermore, when the second target is missed, other processes (i.e., Target 1 processes) must be occupying capacity-limited processing space; and the access of second target information to some of the more advanced processing levels is deferred. Other electrophysiological measures that indicate different subprocesses are for example the event-related potentials P1 and N1 whose factor-related modulations are measures of perceptual processing (Hackley, Woldorff, & Hillyard, 1990; Mangun, Hillyard, & Luck, 1993; Regan, 1989). Visual-attentional processes can be measured by investigating differences in modulation of the N2pc (Brisson & Jolicœur, 2007a, 2007b; Eimer, 1996; Luck and Hillyard, 1994, Woodman & Luck, 2003). Motor-response preparation processes are reflected by modulations of ongoing activity that is commonly referred to as the lateralized readiness potential (LRP) that measures response preparation (Coles, 1989; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988).

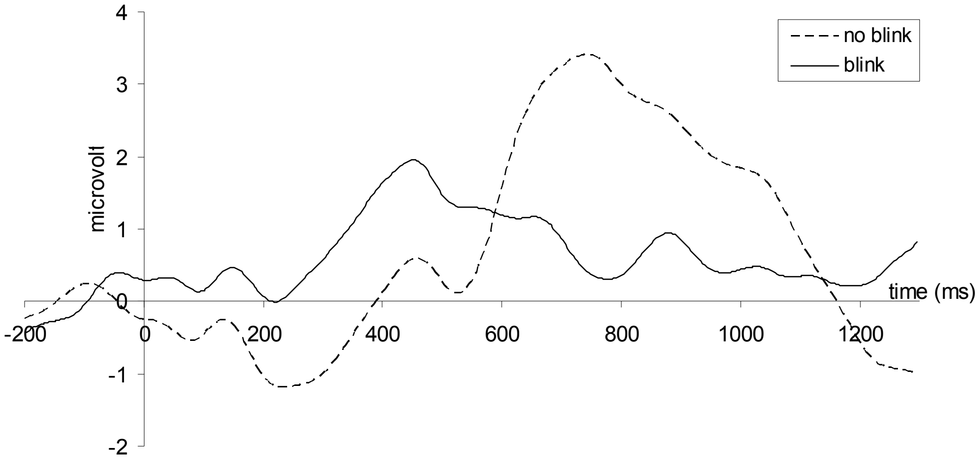

Figure 1.5. An example of an event related potential waveform measured over the medial posterior side of the head. Target 2 is presented at 360 ms and the P3 starts to rise 400 ms later at 750 ms with a peak at 900ms. The dotted line represents the correct (no-blink) trials and is high in amplitude. The bold line represents the incorrect (blink) trials and is heavily attenuated (Pannebakker, Band, Ridderinkhof, & Hommel, 2007).

Process overlap in dual tasks

The separation of the information processing stream into different subprocesses from stimulus presentation to response has helped the investigation of the source of dual-task slowing. Dual-task slowing appears when two (sub-) processes cannot be conducted concurrently (i.e. in parallel) and cause a delay. The prime objective in dual-task research has been to see which processes show no slowing – could be conducted in parallel – and which processes did. Processes prone to dual-task slowing can be identified by independently changing the subprocesses. Research has shown that capacity-limited processes cause other capacity-limited processes to be put on hold. The location of this limitation process was identified as the response selection segment in Sternberg’s model. Further research has shown that processes like short-term consolidation (Jolicœur & Dell’Acqua, 1998), mental rotation (Van Selst & Jolicœur, 1994), and memory retrieval (Carrier & Pashler, 1995) are also considered capacity-limited processes. In sum, all subprocesses of the two tasks can be conducted in parallel; except for the combination of T1 capacity-limited processes and T2 capacity-limited processes.

Attentional processes like visual-spatial attention have also been investigated on whether they have capacity-limited properties. Results from behavioural research showed that visual-spatial attentional processes do not cause interference in a dual task, and therefore visual-spatial attention was assumed not to be capacity limited (Johnston et al., 1995; Pashler, 1991). Recent electrophysiological research (using the N2pc as an electrophysiological measure) however, showed that there was indeed a postponement of visual-spatial attentional processes by limited-capacity processes of a preceding task (Brisson & Jolicœur, 2007a; 2007b). Research in this thesis will investigate whether these recent results can be extended to other capacity-limited processes than the one used in Brisson and Jolicœur (2007a; 2007b).

For processes that are known to be capacity limited, we can predict how the modulation of the different subprocesses would affect RT2 (see Figure 1.6), with different predictions for short and long SOAs and for serial and parallel capacity-limited processing. During T1 capacity-limited processes (block β) at short SOAs, T2 perceptual processes (block α) are likely to have finished and T2 capacity-limited processes (block β) are on hold, creating waiting-time or slack-time for T2 (see Figure 1.6A). At long SOAs, T2 is presented later in time, and therefore the slack-time will be shorter or non-existent (see Figure 1.6B). Because T2 capacity-limited processes can only commence after T1 capacity-limited processing has finished, RT2 will be longer at short SOAs compared to long SOAs. Any manipulation of perceptual processes will have an effect that is absorbed by the slack-time and will therefore not fully affect RT2. Thus, the effect of perceptual difficulty will be underadditive to the effect of decreasing SOA. T2 manipulations that tax capacity-limited processes, such as the complexity of a stimulus-response translation rule will have an effect that is *additive* to the effect of decreasing SOA. That is because in case of serial processing the starting point of T2 capacity-limited processes is always the same: at the end of the T1 capacity-limited processing (see Figure 1.6A). If (partial) parallel capacity-limited processing occurs, T2 capacity-limited processing doesn’t have to wait for T1 capacity-limited processing to finish and a shorter SOA would not linearly affect RT2. This results in an *underadditive* effect for RT2 at short SOAs compared to long SOAs (see Figure 1.6C). At long SOAs, there is no slack-time and T2 processes experience no delay (because T1 capacity-limited processes have finished before T2 perceptual processes have finished), which is manifested in an additive effect (relative to the short SOA situation) and to an overall smaller RT2 (relative to RT1) (see Figure 1.6B and 1.6D).

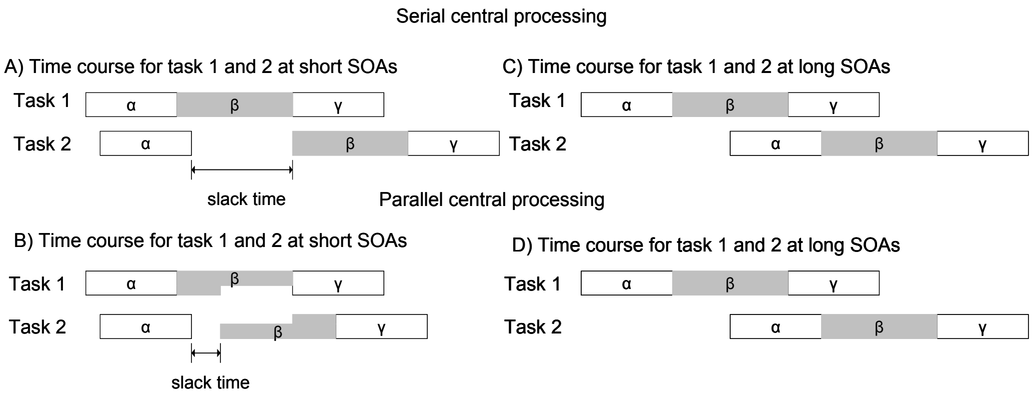

Figure 1.6. An overview of the time course of the serial processing model and the parallel processing model for short and long SOA

In sum, the serial capacity-limited processing model and the parallel capacity-limited processing model can be distinguished by their performance on T2 for short SOAs. The serial capacity-limited processing model predicts an additive effect of RT2 with decreasing SOA because T2 processing has to wait for T1 capacity-limited processing to finish. The parallel capacity-limited processing model predicts an underadditive effect of RT2 with decreasing SOA because T2 capacity-limited processing can start before T1 capacity-limited processing is finished.

These predictions have been tested and the results show evidence for both models, although more evidence is available for parallel capacity-limited processing models. Research supporting the serial capacity-limited processing model was proposed by Carrier and Pashler (1995) who conducted a PRP paradigm in which T1 was a tone discrimination and T2 was an episodic memory-retrieval task. Tone discrimination was made between a high and a low tone. In the memory-retrieval task, participants practiced words that later had to be recalled in the test phase. Results show that when SOA was shorter, RT2 became longer; this effect was additive for RT2. Carrier and Pashler (1995) argued that this dual-task slowing was caused by a response-selection bottleneck that postponed S2 response-selection processes (but not any other processes like perceptual or motor processes).

Results supporting the parallel capacity-limited processing model were conducted by Van Selst and Jolicœur (1994) who also used a PRP paradigm, in this case with tone discrimination task (T1) and mental rotation task (T2). In a mental rotation task, a stimulus - often a letter or a digit - can be presented in normal or mirror image. This normal/mirror discrimination takes longer when the stimulus is in a greater angle from upright (Corballis, 1986). Results showed a delayed RT2 for shorter SOA, but this delay was underadditive with SOA implying parallel processing up to some extent. Moreover, Van Selst and Jolicœur (1994) found that varying the angle from upright in the mental rotation task - thereby varying working-memory load - influenced RT1. This is an indication that mental rotation started before R1 selection. Any influence of T2 processes on RT1 is an indication of activation of particular T2 subprocess before T1 capacity-limited processing has finished, which can only be explained by a parallel capacity-limited processing model. In sum, a processing delay occurs in dual tasks, although parallel processing up to a certain extent is possible.

Limitations: structural vs. functional

At the start of the introduction I have discussed how talking on the phone is the most convenient when you are sitting on the settee, giving the person you talk to your full attention. When talking on the phone takes place concurrently with another activity, in this case driving, this can affect your ability to drive as well as your ability to talk on the phone. This impairment will be bigger when the tasks are more demanding, or take up more working memory. Apart from the effect of working-memory load, the combination of tasks can also affect how well two tasks can be conducted together. For example, talking on the phone can be combined more easily with driving than with listening to a third person. Similarly, when dual tasks are studied, limitations can be due to working-memory load or capacity limitations, or they can be due to feature- or process-combination limitations. The former has been studied in research that is focused on limitations of the task load and the capacity of processing hardware, that is structural processing limitations. The latter has been studied by investigating whether the combination of the task properties (features or processes) or for example the strategic settings during a task can increase performance given the same task load, which points to functional processing limitations.

Some dual-task models explain the dual-task delay solely by structural processing. One example is an experiment by Tombu and Jolicœur (2002), who suggested a graded form of capacity sharing (see also: Kahneman, 1973; Navon & Gopher, 1979; Navon & Miller, 2002). In their experiment, they presented a tone task (T1) and a discrimination shape-matching task (T2) in a PRP paradigm. The stimuli in T2 were two polygons presented in three possible sizes. Participants were required to make a mirror/same judgment by comparing the two polygons and ignore the difference is size. T2 difficulty was manipulated by changing the size ratio of the two presented shapes-to-match as an increased ratio results in a longer RT (Bundesen & Larsen, 1975; Jolicœur & Besner, 1987). Results showed an additive effect of T2 difficulty with SOA suggesting that shape-matching processes were sensitive to a response-selection bottleneck. At the same time, RT1 varied with SOA indicating that T2 capacity-limited processes were activated before T1 response decision was made, which was taken to suggest that T2 processes started at the cost of a longer duration of capacity-limited processes of T1.

Other dual-task models take into consideration that combinations of different features or processes can also influence the size of the dual-task delay (functional processing limitations) (Hommel, 1998; Logan & Schulkind, 2000). Hommel (1998) conducted a series of dual-task experiments in which he investigated the contribution of functional processing limitations to dual-task slowing. He presented a red or green H or S that required a manual response to the color (T1) and vocal response to the letter (T2). The two responses could be compatible or incompatible, i.e., pressing left and saying “left” would be considered compatible while pressing left and saying “right” would be considered incompatible. The backward-compatibility effect compared the effect of compatible versus incompatible feature-response combinations at RT1. Results showed a facilitation effect for RT1 (i.e., less dual-task slowing) in case of compatible responses. This could only occur when R2 is activated before S1 response selection. Any effect of R2 features on RT1 is direct evidence for parallel processing. More importantly, in the experiment by Hommel (1998), the working-memory load of the compatible and the incompatible conditions did not differ: there were no differences in structural processing limitations. However, the combination of features did differ; the key press and the vocal response could be compatible or incompatible. Therefore the functional processing limitations were different. Because there was no difference in working-memory load, any difference in the dual-task delay could be attributed to the features of the stimuli and how they were combined. Whether compatibility between processes would also show facilitation, independent of task load, has not yet been investigated and will be one of the aims of this thesis.

Aims of thesis

Research up to now has shown that dual-task paradigms like the PRP can be used to investigate working-memory limitations. Furthermore, research has already shown that the delay that occurs when two tasks are conducted simultaneously can be due to structural processing limitations, and recently, also some functional processing limitations of dual-task processing have been identified. However, we still do not know the exact nature of the delay in dual tasks. The general aim of this thesis was to investigate the functional limitations in dual-task processing, to obtain a better understanding in the reason why they occur and to what extent they are limited, in the relation between different dual tasks, in the attentional processes involved during dual-task processing and in working memory in general. More specifically the purpose was to:

1. investigate the relative contribution of functional limitations in the backward-compatibility effect in a dual task;
2. explore the relation between the dual-task costs that occur in the PRP paradigm and in the AB paradigm. Additionally, it was explored whether the dual-task limitations in the PRP and AB paradigm can be explained by similar factors. This was accomplished by investigating the correlation between PRP, AB, working-memory operation span and IQ to examine the role of working-memory operation span in the two paradigms (independent of IQ);
3. investigate the process overlap in a dual task between mental rotation and visual-spatial attention electrophysiologically to clarify whether attention can be used independent of capacity-limited processes, or whether they might share a common resource;
4. explore whether an additional working-memory load affects the relative contribution of functional limitations in the backward-compatibility effect in a dual task. Additionally, the purpose was to investigate which processes (i.e. so-called implementation processes and execution processes) in a dual task other than response selection are capacity limited.

Outline of thesis

This thesis consists of four chapters (Chapters 2-5) reporting empirical work on dual-task limitations.

In the second chapter, the effect of backward compatibility between processes in a PRP paradigm is investigated. In the first experiment, we present two mental-rotation tasks and vary rotation compatibility (by compatible or incompatible rotation direction) and category match (both mirror or both normal for match; mirror and normal for mismatch) orthogonally. Results show that parallel processing can be modulated by the response match between categories, but only in case of rotation compatibility between tasks (and not in case of an incompatibility). This suggests that only one rotation process can be active (either clockwise or counterclockwise rotation) but that this process can be applied to (at least) two stimuli. When this happens, property information of S2 (i.e. category-response match) can influence RT1, and in case of matching response categories there is a facilitation. When the two processes are incompatible, S2 won't be activated because only one process can be activated at the time. These circumstances do not allow for T2 category-response match to influence R1. The second experiment investigates a similar situation, but S2 is replaced by an upright stimulus that moved in an irrelevant path around S1. In this case, T2 is low in task load. Still, category response match facilitates R1 in case of rotation compatibility.

In the third chapter, a study is presented of the correlation between the PRP effect, the AB magnitude and two factors that can predict PRP and AB performance to some extent: working-memory operation span and IQ. Results show a correlation between performance on PRP and AB paradigms: participants with high dual-task costs in the PRP also show a greater difficulty to report T2 in the AB (at intermediate lag). Furthermore, both the PRP effect and the AB magnitude show a correlation with working-memory operation span: people who score high on working-memory operation span have a better PRP and AB performance. In case of the AB magnitude but not the PRP effect, this is independent of IQ performance. This suggests that at least some but not all variance in the two effects is unique to a paradigm.

In the fourth chapter, the effect of a specific capacity-limited process, mental rotation, on T2 visual-spatial attention is examined. The ERP-components N2pc –a measure of the deployment of attention– and sustained posterior contralateral negativity (SPCN) –a measure of the arrival of information into visual short-term memory– are taken to measure attentional delay. Results show that increased difficulty in T1 mental rotation delays succeeding visual-spatial attention. This suggests that mental rotation and visual-spatial attention share capacity-limited properties.

In the fifth chapter, the modulation of process-compatibility effects by working-memory load is investigated. Just as in Chapter 2, a PRP paradigm is presented with two mental rotation tasks; effects of rotation compatibility and category match are measured. An additional working-memory task – involving either a high or low working-memory load – is presented at the start of the trial, and the information is kept active for recall at the end of each trial. Results show facilitation for category-match trials only if the rotations are compatible, confirming Chapter 2 results. This interaction is not affected by the working-memory load. Working-memory load does, however, reduce the category-match effect. This suggests that stimulus activation – which leads to response facilitation in case of compatible mental-rotation directions – does not take up significant working-memory space, but the results of these operations do. The aim of the second experiment is to specify which part of mental rotation causes the delay. Thereto, a PRP paradigm is presented in which two stimuli both require mental rotation. To investigate whether mental rotation can be separated in an implementation process and an execution process, a cue is presented at the start of each trial to validly predict the second stimulus 75% of the time. Only if participants are able to implement the cue before S2 is presented, we would expect faster S2 responses when S2 is validly predicted by the cue compared to when the cue is an invalid predictor. Results suggest that two operations can be implemented simultaneously, but only if the two processes are rotated in the same direction.

The work reported in the four empirical chapters in this thesis has been submitted or accepted for publication. The list is presented below to acknowledge the valuable contributions of the co-authors.

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Pannebakker, M.M., Colzato, L.S., Band, G.P.H, & Hommel, B. (submitted). What do PRP and AB have in common? *Experimental Psychology.*

Pannebakker, M.M., Jolicœur, P., Van Dam, W., Band, G.P.H., Ridderinkhof, K.R., & Hommel, B. (in prep). Does mental rotation affect T2 spatial attention in a dual task?

Pannebakker, M.M., Band, G.P.H., & Hommel, B. (in prep). Capacity limitations of cognitive operations.

Chapter 2

Process Compatibility: A Neglected Contribution to Dual-Task Costs

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Abstract

Traditionally, dual-task interference has been attributed to the consequences of task load exceeding capacity limitations. However, we demonstrate that in addition to task load, the mutual compatibility of the concurrent processes modulates whether two tasks can be performed in parallel. In two psychological refractory-period (PRP) experiments, task load and process compatibility were independently varied. In Experiment 1, participants performed two mental rotation tasks. Task load (rotation angle) and between-task compatibility in rotation direction were varied. Results suggest more considerable parallel execution of compatible than of incompatible operations, arguing for the need to attribute dual-task interference not only to *structural* but also to *functional* capacity limitations. In Experiment 2, it was tested whether functional capacity limitations to dual-task performance can be caused only by demanding processes or whether they are also induced by relatively automatic processes. It was found that an irrelevant circular movement of Stimulus 2 interfered more with mental rotation of Stimulus 1 if the rotation directions were opposite than if they were equal. In conclusion, compatibility of concurrent processes constitutes an indispensable element in explaining dual-task performance.

Introduction

Performance on demanding tasks is known to be limited by temporal overlap with other demanding tasks. Although it is common practice to depict processing limitations in terms of task load, the current study takes the perspective that the notion of task *load* is in itself insufficient to predict the extent to which two tasks can be performed simultaneously. We study the relative contribution of task *content*, and in particular inter-task compatibility to concurrent processing and show that this is another important but neglected dimension in dual-task research. Task content is defined here as task features that do not contribute to task load, but nonetheless contribute to the extent to which two tasks can be performed simultaneously.

Research on dual tasks has shown that when two tasks are presented in rapid succession, the reaction time to the second stimulus (RT2) is increased, while the reaction time to the first stimulus (RT1) is much less affected, compared to conditions without temporal overlap. The effect of stimulus onset asynchrony (SOA) on RT2 is attributed to interference of task 1 (T1) processes onto task 2 (T2) processes and is called the Psychological Refractory Period (PRP) effect. This effect is shown to be very robust (e.g., Logan & Schulkind, 2000; Meyer & Kieras, 1997a, 1997b; Pashler, 1994; Van Selst & Jolicœur, 1994).

Several models have tried to account for the PRP effect. Most of these emphasize structural processing limitations. Structural processing limitations are determined by the combination of the task load and the capacity of processing hardware. As a result, such limitations are not diminished by a different way of performing on a task or by varying the compatibility between them. For example, limited-capacity models assume that the PRP effect reflects the delay that occurs when the sum of processing demands required for separate tasks exceeds the available capacity.

Few models take into account that the combination of operations can also induce processing limitations. We will refer to such limitations as functional processing limitations, defined here as processing limitations imposed by the emergent properties of a combination of two tasks beyond the properties of the tasks separately. The associated costs may be attributed to strategic settings, additional cognitive control requirements, or to interference caused by crosstalk between concurrent processes. This definition implies that given the same task load, some task combinations are easier to perform simultaneously than others. Even though crosstalk can reduce dual-task costs by optimizing the circumstances for parallel processing, it can also open the door for stimulus or response conflict, resulting in increased dual-task costs. When the latter happens, the system could shift from a more parallel mode of processing to a more cautious, serial mode of processing. In this way, when features or processes are less compatible, the deployment of parallel processing will decrease.

Structural-limitation models

Structural capacity limitations have been postulated in several dual-task models. Some of these assume all-or-none use of the available capacity, whereas others assume that capacity allocation can be graded. According to the *structural-bottleneck model*, there are fixed limitations to parallel processing that affect only central processes such as decision making or mental rotation. Such bottleneck processes of T2 can only start after the bottleneck processes of T1 have finished (Pashler, 1994, see also: Keele, 1973, Kerr, 1973, Welford, 1967). The idle time in T2 processing between the offset of pre-bottleneck and the onset of bottleneck processes (slack) is thought to determine the size of the PRP effect. A reduction of SOA will lead to an increase of slack and consequently longer RT2, whereas on longer SOAs there is no slack and RT2 is relatively short.

Carrier and Pashler (1995) introduced the so-called locus of slack logic to distinguish between pre-bottleneck and bottleneck processes. Because bottleneck processes cannot continue during slack, changes of the duration of bottleneck processes will have the same effect on conditions with and without slack. In contrast, pre-bottleneck processes of T2 can continue while bottleneck processes of T1 are taking place. Therefore, experimental manipulations of pre-bottleneck process duration will be absorbed by the slack and will have a smaller effect on RT2 at short SOAs (where slack is present), than at long SOAs (where slack is absent). This pattern of results translates into an additive effect of decreasing SOA and any factor that affects the duration of bottleneck processes, but an underadditive effect of decreasing SOA and any factor that prolongs the duration of pre-bottleneck processes.

Ruthruff, Miller, and Lachman (1995) investigated whether mental rotation qualifies as a bottleneck process. In four PRP experiments using sound discrimination for T1 and a mental rotation task for T2, they observed additive effects in three, and underadditive effects in one experiment. They concluded that mental rotation requires a bottleneck system and that the results give evidence for a single-channel mechanism like the structural bottleneck model (but see: Van Selst & Jolicœur, 1994; Heil, Wahl, & Herbst, 1999; Schumacher et al., 2001).

Van Selst and Jolicœur (1994) used a similar task as Ruthruff et al. (1995) investigating the effect of mental rotation (T2) on T1 processes. Earlier research on mental rotation (Corballis, 1986) had established that mirror/normal discrimination in a mental rotation task can only occur after the rotation has taken place. Van Selst and Jolicœur showed that RT1 was affected by T2 rotation angle, suggesting that T1 processes were slowed down by mental rotation in T2. This result is consistent with *central capacity sharing models,* which assume that demanding processes can run in parallel, but that parallel processing is limited by the load of concurrent tasks relative to the available processing capacity (Bornemann, 1942; Kahneman, 1973; Navon & Gopher, 1979; Navon & Miller, 2002; Norman & Bobrow, 1975; Tombu & Jolicœur, 2003).

Functional-limitation models

Functional-limitation models are a category of models that assert that the relationship between two tasks influences the amount of dual-task costs, independent of task load. They attribute dual-task interference, at least in part, to changes invoked by the combination of tasks involved: some combinations facilitate parallel processes, attenuating the interference. Although they are related in the sense that they do not focus on processing load -like structural models- there are also differences between functional models in explaining in what way this limitation occurs.

The first type of functional limitation involves the delay imposed by coordination over the tasks that are combined. Meyer and Kieras (1997b) argued in their adaptive executive control (AEC) models that central processes such as response selection can take place in parallel. Perfect time sharing (Schumacher et al., 2001) may even be possible with certain task combinations if subjects engage in performing with the appropriate strategy. Nonetheless, subjects usually show performance that is more consistent with serial processing. According to Meyer and Kieras (1997a), deferment of T2 is a way to accomplish the instructed task goal and reduce the risk of errors that is inherent in certain task combinations. This deferment causes RT2 to be delayed on short SOAs, but the size of the delay depends on the content of the concurrent tasks.

Consistent with AEC models, Luria and Meiran (2005) argued that task overlap is modulated by control demands. In two PRP experiments, they varied control demands by a task switch and T1 response selection difficulty by number of response alternatives. The carry-over effect of T1 selection difficulty onto RT2 was used as a measure for parallel processing. Results show a carry-over effect on switch trials, but not on repeat trials. This led Luria and Meiran to argue against structural limitation of parallel processing; instead they suggested that a higher control demand shifts the processing from parallel to serial.

The second type of functional limitation involves the delay imposed by the control requirement in the transition from one task to another, such as proposed in the *Executive Control Theory of Visual Attention (ECTVA,* Logan & Gordon, 2001). According to ECTVA, there are three effects at work in the PRP task; concurrence costs, set switching costs and crosstalk. Concurrence costs involve the extra time required for keeping more than one task set active, and are independent of the relationship between tasks. However, set switching costs vary with the number of parameters that require adjustment. Finally, crosstalk between two tasks occurs if the tasks involve overlapping stimulus or response sets. Because the priority is never fully assigned to processing one stimulus and not the other (cf. the capacity allocation policy, Tombu & Jolicœur, 2003), the set of one task may be applied to the stimulus from another task.

Finally, the third source of functional limitations stems from the interaction at the representation level between feature codes belonging to two concurrent tasks. Features that are activated by one task can interfere with feature representations for another task. This leakage of information between channels is commonly referred to as crosstalk (e.g., Hommel, 1998; Logan & Schulkind, 2000). When two tasks facilitate each other, an increase of parallel processing occurs, while interference because of crosstalk would give rise to a more serial modus of processing. As much as conflicting information between an irrelevant and a relevant channel *within* a task renders a response slower and more error prone (Stroop, 1935; Simon, 1969), features can also affect performance *between* tasks. A requirement for interference seems to be the presence of dimensional overlap (Kornblum, Hasbroucq, & Osman, 1990) between competing codes. For example, activation of a left-hand code interferes with the activation of a right-hand code, but not with an unrelated vocal response because these are not mutually exclusive.

An obvious source of interference following crosstalk is the competition between concurrently activated response codes (e.g., Stoet & Hommel, 1999), but interactions have also been shown between feature codes belonging to stimuli and those belonging to responses. Müsseler and Hommel (1997), for example, showed that observing the direction of an arrow was impeded by the simultaneous planning for a response on the same side. This and other observations have led to the postulation of a unified coding environment for all active features; both stimulus and response features, by the theory of event coding (TEC; Hommel, Müsseler, Aschersleben, & Prinz, 2001). TEC predicts that dual-task costs due to concurrently activated features are modulated by the correspondence of these features.

Backward compatibility and the category-match effect

Support for the predictions of TEC for PRP performance comes from Hommel (1998), who showed in a series of dual-task experiments that RT1 was sensitive to the match between S1 and R2. For example, in Experiment 2, colored letters were presented, and subjects were to respond first to the color, and then to the identity. Because the vocal response to the identity of the letter was the word “red” or “green”, there was feature overlap between S1 and R2. Hommel found longer RT1s to a nonmatching S1-R2 combination (e.g., GREEN-RED) than to a matching combination (e.g., GREEN-GREEN).

Hommel's (1998) results are a clear sign of crosstalk between the two tasks. Moreover, crosstalk occurred between stimulus and response representations, consistent with the TEC notion of a unified encoding environment. This notion also plays an important role in Experiment 2 of the current study, in which crosstalk between stimulus representations and concurrent operations is demonstrated.

The match effect that Hommel (1998) reported also has implications for the plausibility of strictly serial models. The effect from T2 processes onto RT1 implies that stimulus classification processes (like decision and selection processes) of T1 only finished after R2 was activated. It demonstrates that response activation processes can run in parallel, and that concurrent task content affects the speed of mental operations in a dual task.

An important methodological innovation of Hommel's (1998) study is that it demonstrated parallel processing with priming effects of T2 features onto RT1. This technique has been developed further by Logan and Schulkind (2000). They tested whether semantic memory retrieval can happen in parallel for two alphanumeric stimuli presented on either sides of the center that had to be classified as letter vs. digit. Consistent with Hommel's (1998) results, matching response categories (digit-digit or letter-letter) led to a shorter RT1 than mismatching response categories (digit-letter or letter-digit). Logan and Schulkind concluded that, at least when two similar tasks are combined, R2 information becomes available before R1 is selected. Due to crosstalk, the similarity between response categories affects the speed by which R1 is selected. Category-match effects are typically even larger on RT2 than on RT1, but RT2 effects can not exclusively be attributed to crosstalk taking place during parallel processing.

The category-match effect is a robust finding that has been replicated with a variety of task combinations (Band & van Nes, 2006; Logan & Delheimer, 2001; Logan & Gordon, 2001; Lien, Schweickert, & Proctor, 2003). It is therefore suited to demonstrate differences between conditions in the degree of parallel processing. In the current study we adopt the category-match effect as an index of parallel processing in tasks that involve the same versus opposite operations.

Current experiments

In this paper, we aim to investigate the relatively unrecognized contribution of task content as a factor in the explanation of dual-task interference. We expect that the task content of two competing tasks modulates the extent to which tasks can be performed in parallel. In particular, the compatibility between operations involved in both tasks will modulate dual-task performance. We manipulated the task content and task load independently with a mental rotation task (Shepard and Metzler, 1971) which invokes the imagined turning of a tilted stimulus to an upright position. This process needs to be executed before the subject is able to decide whether the stimulus is in normal- or mirror-image (Corballis, 1986). Task difficulty (or task load) was varied by changing the angle between the rotated and the upright position.

Task content was varied by having to rotate the stimuli clockwise (CW) or counter clockwise (CCW) to upright position, in variable combinations for T1 and T2. This manipulation does not influence task difficulty: the amount of cognitive effort to mentally turn a stimulus 120 degrees CW or CCW is assumed to be equal. The task content *does* differ, however, between rotating two stimuli in the same versus opposite directions, where the compatibility of rotations is an emergent property of the combination of tasks. Structural-limitation models, which explain dual-task costs by capacity limitations, do not predict an effect of task content whereas functional-limitation models would predict that compatible rotations facilitate parallel processing.

The most important measure in this study is the size of the category-match effect on RT1. First of all, it is predicted that subjects respond faster to a tilted stimulus if the relevant stimulus category, that is normal- versus mirror-image, is equal for S1 and S2. Because judgment of the image is contingent upon mental rotation (see Corballis, 1986), the observation of a category-match effect would imply that mental rotation, response selection, or both take place in parallel for both tasks. Because both mental rotation and response selection are demanding processes that have been associated with the central bottleneck (Ruthruff et al., 1995; Van Selst & Jolicœur, 1994), a significant category-match effect would be evidence against an all-or-none bottleneck and in favour of parallel processing. Next step would be to differentiate which processing steps (i.e. mental rotation, response selection or both) would be facilitated or impeded with different conditions of the match effect.

Second, experimental modulation of the category-match effect would imply that parallel processing can be increased or decreased. Because we manipulate both task content and task load, it is possible to measure independently whether these factors affect processing limitations and to what extent.

Response codes become available contingent on mental rotation and response activation, so if the match between R1 and R2 codes influences RT1, this implies that the R2 code becomes available before the R1 is determined. This implies that at least mental rotation and possibly also response activation is performed in parallel. The match effect is defined as the difference in RT1 on normal/normal and mirror/mirror combinations versus RT1 on normal/mirror and mirror/normal combinations, that is between trials with matching and mismatching response categories. Restrictions to parallel processing, for example due to the incompatibility of operations, can be expected to cause a reduction of the match effect.

As discussed, some functional limitation models predict that compatibility between features involved in concurrent tasks contribute to the ability to process two tasks in parallel. Whether this also applies to the compatibility between operations is an empirical question that is addressed in this study.

It is important to note that rotation compatibility as such is not responsible for yielding preliminary information about R1 or R2. It should not be confused with the category-match effect. When two stimuli require mental rotation in the same direction, they equally often require opposite and same responses.

Experiment 1

Methods

Participants

Thirty students (six male) of Leiden University participated in this experiment that took three sessions of 1.5 hours. The mean age was 21 years (*SD* = 2). The experiment was conducted in accordance with relevant laws and institutional guidelines and was approved by the local ethics committee from the Faculty of Social Sciences. One student indicated to be left-handed, the remaining were right-handed. All students had normal or corrected to normal eye-sight. They received either thirty-six euros or course credits or a comparable combination of both. Data from two participants were excluded from analysis as there were too few trials in some conditions.

Apparatus

Participants were tested individually, in separate booths in the Cognitive Psychology Lab. The booth was dimly lit, and participants were sitting in front of a 17 inch computer screen with a viewing distance of approximately 75 cm. Responses were made with key-presses on the bottom row keys of the computer keyboard; the left hand operating the z- and x-button and the right hand operating the n- and m-button of a QWERTY keyboard.

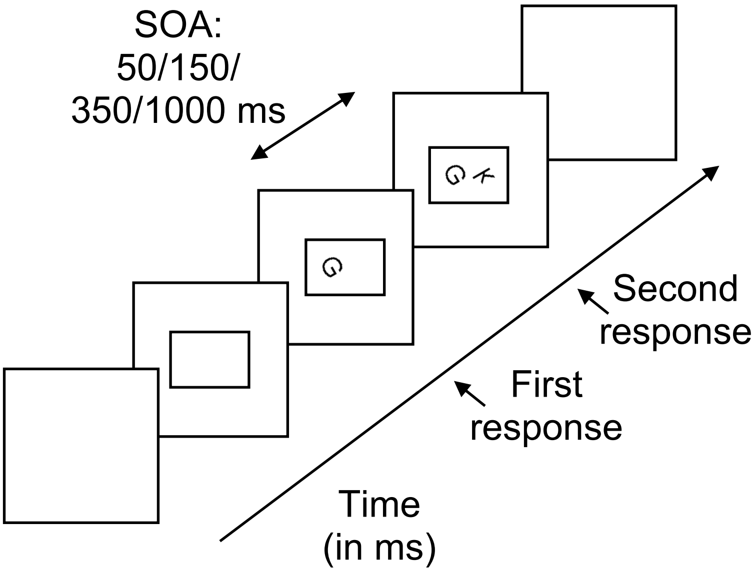

Figure 2.1. Sequence of events within one trial in Experiment 1: the rectangle serves as a fixation, in which S1 appears left from the middle, and after a variable SOA S2 appears right from the middle

Stimuli

For the stimuli presented on the screen, the alphanumeric characters 2, 4, 5, 7, f, G, k, Q and R were used in both tasks. These stimuli were selected because their asymmetry allows the creation of unambiguous rotation and mirroring conditions. They were oriented either normally or mirror-imaged and their orientation was 0, 60 or 120 degrees. CW and CCW tilted stimuli occurred equally often. The characters were presented in black on a white screen within a black-lined rectangle. Because this was a dual task, two characters were presented within the rectangle with a visual angle of 5.8° × 3.6° (horizontal × vertical). Stimuli were presented well within the boundaries of this rectangle. The two presented stimuli were separated by a SOA of 50, 150, 350 and 1000 ms. SOA, mirror/normal image of characters, response category match/mismatch, rotation direction, and angle of rotation were all varied randomly within blocks.

S1 always appeared left from the middle and called for a left-hand response, S2 always appeared right from the middle (see Figure 2.1) and called for a right-hand response. The mapping of normal/mirror image to index/middle fingers was balanced between subjects. A normal image required either the left finger (‘z’ or ‘n’ key) or the outer finger of each hand (‘z’ or ‘m’ key). A mirror image required either the right finger (‘x’ or ‘m’ key) or the inner finger of each hand (‘x’ or ‘n’). Thus, a confound between the category match effect and the benefit of using homologous fingers was prevented.

Procedure

Before the start of the experiment, participants received a written instruction. They were asked to respond as quickly as possible, and not to be too cautious in their response. No reference was given as to which stimulus had to be responded to first. Then more explanation was presented on the computer followed by three practice blocks, after which the experimental blocks started. The first practice block was a single-task practice for the left hand, and the second one was a single-task practice block for the right hand. These two blocks contained 20 trials each. The third block was a dual-task block session that consisted of 40 trials.

Experimental trials were presented in 14 blocks of 90 trials. Pauses separated the blocks and participants were encouraged to use them. Within the experimental blocks, the trial started with the presentation of a black rectangle for 250 ms in the middle of the screen (see Figure 2.1). Then, two stimuli appeared on either side of the middle of the rectangle, separated by a variable SOA. As soon as the stimuli appeared, participants had 8000 ms to respond before the screen automatically turned white. Responding to S2 caused the screen to turn into white immediately. Two correct responses resulted in a ‘+’ feedback response, while any other combinations of responses elicited a ‘-’ feedback response that was in both cases shown for 500 ms at the end of every trial. After a Response-Stimulus Interval (RSI) of 1000 ms the empty rectangle appeared to announce the beginning of the next trial. At the end of each block, an average reaction time (RT) in ms and a percentage correct (PC) over that block was presented to give participants insight on their progress, and to motivate them to keep trying to respond faster on every block.

Results

RTs longer than 5000 ms or shorter than 150 ms and trials in which R2 preceded R1 were excluded from the analysis of RT and PC. The latter was the case in 0.35% of the trials. Mean RTs were based on trials with a correct response to both stimuli. Data were analyzed with repeated measures analysis of variance (ANOVA) using a 2 × 2 × 2 × 2 × 4 design with the within-subjects factors rotation compatibility, category match, angle 1, angle 2 and SOA. Alpha was set at 0.05. The Greenhouse-Geisser Epsilon was used to correct the p and MSE, but original df’s are reported. Table 2.1 and Table

2.2 show the mean performance data. The ANOVA results are summarized in Table 2.3 and Table 2.4.

Table 2.1. Mean reaction times for Task 1 and Task 2 in Experiment 1

	RT1				RT2			
SOA (ms)	50	150	350	1000	50	150	350	1000
Angle1 - Angle 2								
60°-60°	1032	1027	976	865	1262	1160	970	709
60°-120°	1098	1076	981	894	1414	1289	1071	858
120°-60°	1222	1206	1172	1048	1472	1358	1156	789
120°-120°	1264	1258	1048	1064	1577	1471	1233	905
Rotation compatible	1137	1127	1070	974	1407	1299	1093	807
Category match	1116	1104	1058	973	1377	1261	1071	796
Category mismatch	1157	1150	1082	975	1437	1338	1114	819
Rotation incompatible	1172	1157	1090	962	1456	1340	1123	823
Category match	1174	1160	1094	966	1458	1343	1130	836
Category mismatch	1169	1153	1086	958	1454	1336	1115	810

Table 2.2. Mean percentages correct for Task 1 and Task 2 in Experiment 1

	PC1				PC2			
SOA (ms)	50	150	350	1000	50	150	350	1000
Angle1 - Angle 2								
60°-60°	95.5	96.5	96.7	96.5	93.7	94.8	94.9	95.1
60°-120°	96.3	96.5	96.5	96.0	90.0	89.8	90.1	90.6
120°-60°	91.8	92.4	93.3	92.6	93.8	93.1	93.5	93.6
120°-120°	92.6	92.7	93.8	93.0	90.1	89.9	90.3	90.1
Rotation compatible	93.9	94.7	95.0	94.7	91.6	91.5	91.7	92.3
Category match	94.1	95.1	95.1	95.0	91.2	91.6	91.9	92.2
Category mismatch	93.8	94.3	95.0	94.4	91.9	91.5	91.6	92.4
Rotation incompatible	94.2	94.4	95.1	94.4	92.1	92.2	92.6	92.4
Category match	94.2	94.9	95.2	94.4	91.2	91.2	91.4	90.7
Category mismatch	94.3	93.9	95.0	94.4	92.9	93.2	93.9	94.1

Table 2.3. Summaries for Analyses of Variance for reaction times and percentages correct for Task 1 in Experiment 1 for all effects up to second order effects plus the significant higher order effects

	RT1					**PC1**			
Effect	df	MSE	F	p	part. η^2	MSE	F	p	part. η^2
Rotation compatibility (R)	1,27	8083	18.2	<.001	.402	10	.19	.669	.007
Category match (C)	1,27	10186	5.0	.035	.155	22	2.7	.113	.091
R × C	1,27	9717	14.1	.001	.342	15	.23	.638	.008
SOA (S)	3,81	129689	59.8	<.001	.689	93	3.3	.023	.110
R × S	3,81	6655	8.6	<.001	.242	13	.69	.561	.025
C × S	3,81	5572	2.2	.103	.074	17	1.0	.388	.036
Angle 1 (A1)	1,27	58140	262.6	<.001	.907	59	94.5	<.001	.778
R × A1	1,27	10362	3.9	.059	.126	12	.006	.940	.000
C × A1	1,27	10923	.43	.518	.016	17	1.4	.250	.049
R × C × A1	1,27	9810	3.0	.095	.100	9	5.9	.022	.180
S × A1	3,81	9420	2.2	.107	.074	22	.98	.393	.035
Angle 2 (A2)	1,27	25998	20.6	<.001	.433	11	3.4	.076	.112
R × A2	1,27	7309	6.2	0.19	.186	13	.76	.391	.027
C × A2	1,27	7936	.94	.341	.034	11	.018	.893	.001
R × C × A2	1,27	4358	3.2	.085	.106	14	2.1	.162	.071
S × A2	3,81	7209	7.3	<.001	.212	17	1.4	.242	.051
R × S × A2	3,81	6385	.86	.449	.031	16	.71	.543	.026
A1 × A2	1,27	5546	.55	.466	.020	17	1.3	.260	.047
C × A1 × A2	1,27	6421	10.2	.004	.273	20	<.001	.996	<.000
R × C × A1 × A2	1,27	7384	12.8	.001	.322	7	.44	.515	.016
C × S × A1 × A2	3,81	7472	2.6	.070	.088	14	1.7	.187	.058

Table 2.4. Summaries for Analyses of Variance for reaction times and percentages correct for Task 2 in Experiment 1 for all effects up to second order effects plus the significant higher order effects

			RT2				**PC2**		
Effect	df	MSE	F	p	part. η²	MSE	F	p	part. η²
Rotation compatibility (R)	1,27	10667	48.1	<.001	.641	42	3.0	.096	.099
Category match (C)	1,27	30684	5.2	.031	.160	53	13.3	.001	.330
R × C	1,27	8826	51.5	<.001	.656	24	23.1	<.001	.461
SOA (S)	3,81	101057	710.3	<.001	.963	25	1.2	.306	.043
R × S	3,81	7013	3.6	.020	.119	28	.59	.601	.021
C × S	3,81	6495	5.4	.003	.167	27	.75	.505	.027
Angle 1 (A1)	1,27	47059	224.0	<.001	.892	27	4.9	.036	.153
R × A1	1,27	5809	7.8	.009	.224	13	.82	.374	.029
C × A1	1,27	9566	1.6	.220	.055	31	17.2	<.001	.389
R × C × A1	1,27	12433	2.0	.173	.068	23	1.9	.664	.007
S × A1	3,81	9491	44.3	<.001	.622	15	.2.2	.097	.077
Angle 2 (A2)	1,27	34110	182.2	<.001	.871	102	70.5	<.001	.723
R × A2	1,27	9555	3.0	.096	.100	34	28.7	<.001	.515
C × A2	1,27	8932	2.7	.114	.090	21	11.7	.002	.303
R × C × A2	1,27	5646	7.9	.009	.227	14	10.8	.003	.286
S × A2	3,81	9168	6.6	.002	.197	26	.059	.974	.002
R × S × A2	3,81	6604	2.4	.080	.083	19	.94	.417	.034
A1 × A2	1,27	6311	15.8	<.001	.370	18	9.2	.005	.253
C × A1 × A2	1,27	7227	18.0	<.001	.400	23	24.7	<.001	.477
R × C × A1 × A2	1,27	7908	21.9	<.001	.447	16	3.8	.063	.123
C × S × A1 × A2	3,81	6929	2.5	.077	.084	23	1.2	.311	.043

RT1

All the five main effects on RT1 were significant. A main effect of SOA reflected a monotonic decrease of RT1 with increasing SOA (1154, 1142, 1080 and 967 ms). The difference between 60 and 120° was 185 ms for angle 1 and 35 ms for angle 2 in favour of the smallest angle. Participants responded 10 ms faster to matching than to mismatching categories, and 18 ms faster to compatible than to incompatible rotation pairs.

Increasing SOA led to reducing effects of rotation compatibility (from 35 to -12 ms) and angle 2 (from 54 to 22 ms, as shown in Figure 2.2). The often reported reduction of the category-match effect with increasing SOA was only marginally significant (a reduction from 18 to -3 ms). The effect of angle 1 did not vary systematically with SOA.

The pivotal interaction of rotation compatibility × category match was significant (see Figure 2.3). Follow-up analyses showed that the category-match effect was substantial for compatible rotations (29 ms; *F* (1,27) = 12.4, *p* < .01), but not significant for incompatible rotations (6 ms; *F* (1,27) = 1.9, *p* = .182). The effects of rotation compatibility and rotation compatibility × category match were marginally larger if angle 1 was 120 relative to 60°, but significantly smaller if angle 2 was 120 relative to 60°. Furthermore, the category-match effect and the interaction of rotation compatibility × category match were largest if both angle 1 and angle 2 were 120°.

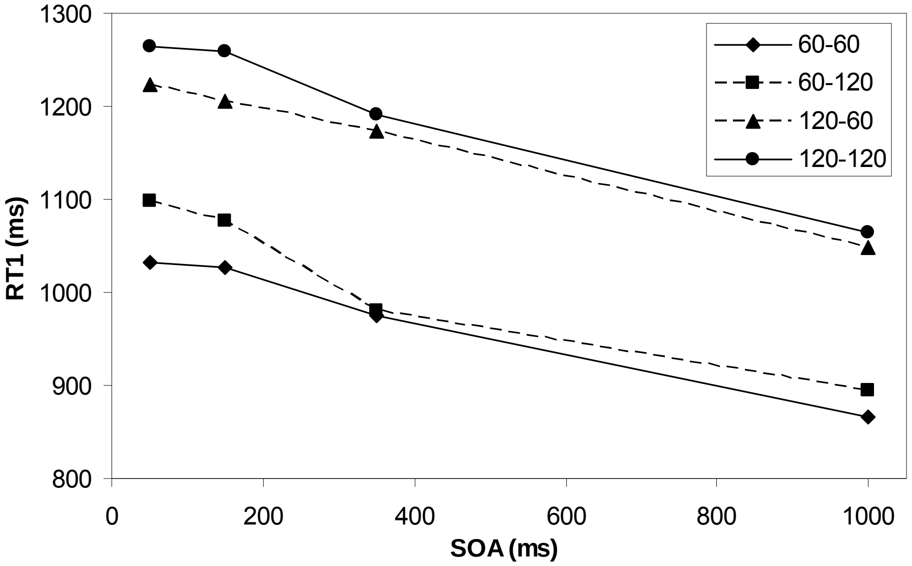

Figure 2.2. The interaction of angle 1, angle 2 and SOA on reaction time 1 of Experiment 1. In this figure, angle 1 and angle 2 are presented in the different combinations that they can occur: both can be tilted 60° or 120°

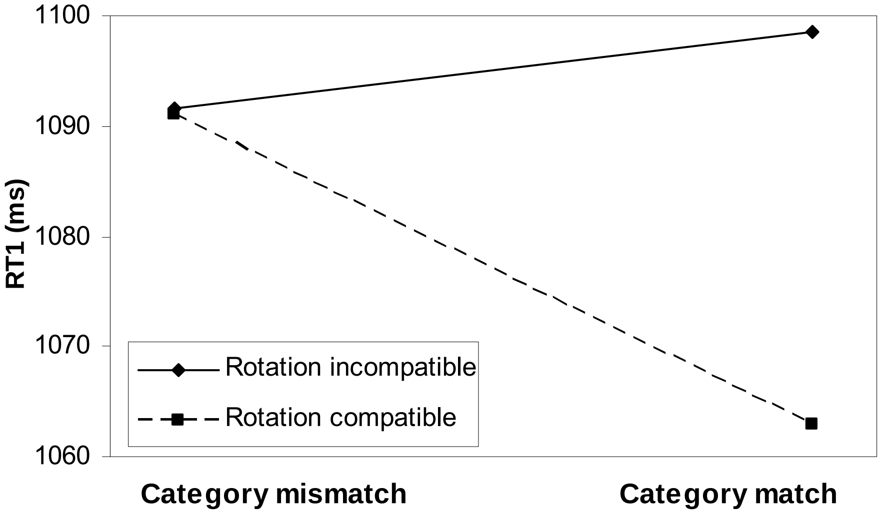

Figure 2.3. The interaction of rotation compatibility and category match on reaction time 1 of Experiment 1

PC1

Only the main effects of SOA and angle 1 were significant. The main effect of SOA was not monotonic, with all levels of PC1 between 94.1% and 95.1%. The main effect of angle 1 was caused by a 3.5% decrease of PC1 going from S1=60° to S1=120°. Interactions of rotation compatibility × category match × angle 1 and of category match × SOA × angle 2 showed no systematic pattern.

RT2

All main effects were significant and in the same direction as for RT1. There was a typical PRP effect; an effect of SOA on RT2, with a monotonic decrease from SOA-50 to SOA-1000 (1431 ms, 1320 ms, 1108 ms, and 815 ms respectively). Effects on RT2 for rotation compatibility (34 ms) and category match (19 ms) were only slightly larger than for RT1. RT2 was 153 ms faster to angle 1 = 60° than to angle 1 = 120°, and the effect of angle 2 was 117 ms in the same direction.

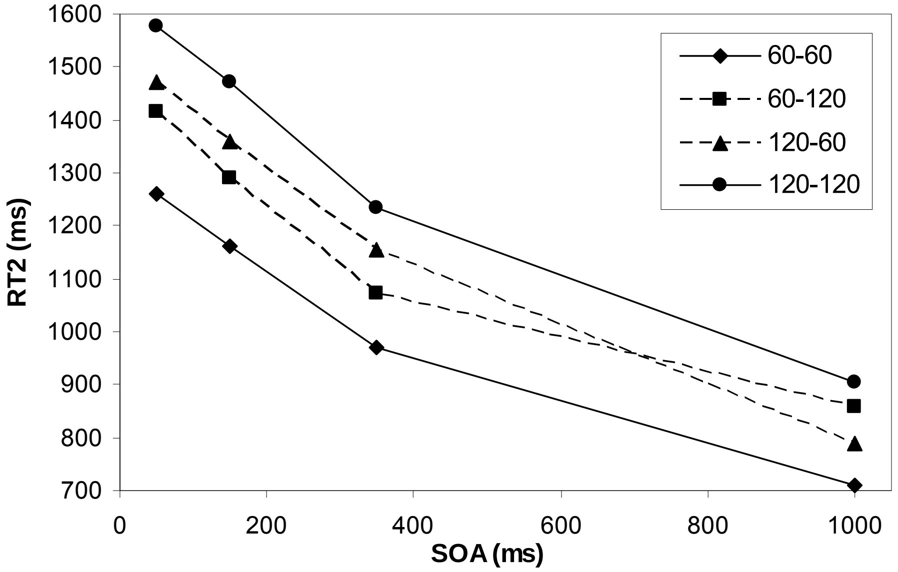

Figure 2.4. The interaction of angle 1, angle 2 and SOA on reaction time 2 of Experiment 1

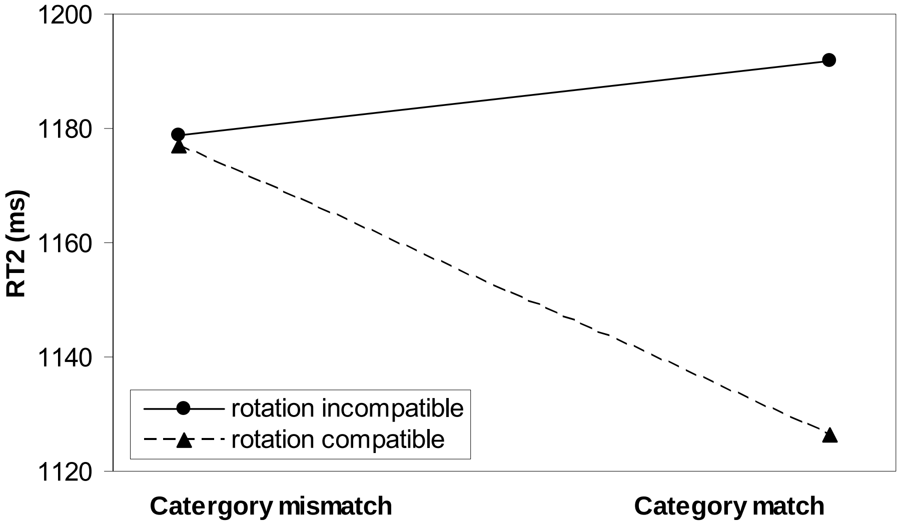

Figure 2.5. The interaction of rotation compatibility and category match on reaction time 2 of Experiment 1

An increasing SOA led to a decrease of the effects of angle 1 (from 187 to 63 ms) and a nonmonotonic changes in the effect of angle 2 (129, 120, 89 and 133 ms, as shown in Figure 2.4). At long, relative to short SOAs, there was a decrease of the effects of rotation compatibility (from 49 to 16 ms) and category match (from 28 to -1 ms).

Rotation compatibility interacted with category match, as is illustrated in Figure 2.5. The category-match effect was larger for compatible rotations (51 ms) than for incompatible rotations (-12 ms). The rotation compatibility effect was larger if angle 1=120° vs. 60° (44 vs. 24 ms) and marginally smaller if angle 2=120° vs. 60° (26 vs. 42 ms). An interaction of rotation compatibility × category match × angle 2 signified that the category-match effect was reversed if S2 had to be rotated in 120° in the opposite direction of S1, whereas all other comparisons showed faster responses to matching response categories.

There was an underadditive interaction of angle 1 × angle 2. This was most of all the case on compatible rotations and with matching response categories, as indicated by the interactions of rotation compatibility × category match × angle 1 × angle 2 and category match × angle 1 × angle 2.

PC2

There were main effects of angle 1 and angle 2 in the expected direction and an interaction of angle 1 × angle 2, showing underadditive costs of rotating both S1 and S2 120°. The category-match effect (1.3%) and the marginal effect of rotation compatibility (0.6%) were both in the reversed direction. An interaction of rotation compatibility × category match was caused by remarkably high accuracy with incompatible rotation and nonmatching response categories.

An interaction of effects of category match × angle 1 × angle 2 was caused by deviating high costs if there was a category match between stimuli with angle 1=60° and angle 2=120°. This pattern also explains the interactions of category match × angle 1 and category match × angle 2.

Discussion

In the experiment, we manipulated central processing load of two mental rotation tasks in a PRP paradigm and investigated the category-match effect as a measure of parallel processing. To distinguish between the two classes of limitation models we independently varied angle as a task load manipulation, and rotation compatibility as a manipulation of operation compatibility. Several results suggest that the high task load of mental rotation as such limited parallel processing. One example is the finding that RT1 was affected by angle 2. This is a result that suggests that an increased T2 load imposed by mental rotation over a larger angle left less capacity available for T1. Apparently, T1 did not receive full priority over T2, as S2 rotation must have taken place before T1 was finished. This suggests that rather than through an all-or-none bottleneck, capacity was allocated to tasks in a graded manner.

More evidence against all-or-none bottlenecks comes from the category-match effect, which implies that the correct response category (mirror vs. normal) for T2 was activated before R1 was selected (Hommel, 1998). The match effect as such might be explained by capacity-sharing models (Navon & Miller, 2002; Tombu & Jolicœur, 2003), but only under the assumption of crosstalk between T1 and T2. One might want to argue that this crosstalk took place without mental rotation and response selection. However, this is hard to account for, given the data: at least some mental rotation took place before R1 was selected, as the occurrence of a category-match effect is contingent on the activation of the R2 category, and decisions about the R2 category are contingent on mental rotation. This implies that mental rotation of S2 started before R1 was selected and affected R1 speed and accuracy.

Modulation of the category-match effect

To test whether task load modulates parallel processing, the difficulty of mental rotation was manipulated. Subjects rotated S2 over 60° or 120°, and the question was whether this affected the category-match effect. The category-match effect was somewhat larger if T1 competed with a S2 rotation of 60° (26 ms) than with a rotation of 120° (12 ms), but not significantly. Furthermore, the interaction of category match and rotation compatibility became somewhat smaller if S1 was tilted 60° compared to 120°; this effect did not reach significance either. These inconclusive findings do not support a modulation of parallel processing by task load as manipulated by the rotation angle. There was a substantial effect of angle 2 on RT1 (53 ms on short SOAs) however, which clearly validates that task load was higher during 120° than during 60° rotation. Thus, while task load affected the efficiency of RT1, it did not modulate the crosstalk from T2 to T1.

Independent of task load, we manipulated operation compatibility. Stimuli could require mental rotation in the same or opposite direction, and the question was whether the compatibility affected the category-match effect. Contrary to the predictions of structural capacity-limitation models, subjects were better able to perform two tasks simultaneously if they involved compatible as compared to incompatible operations. That is, the category match effect was modulated by the compatibility of mental rotation processes of T1 and T2. These results indicate that the effect of the T2 response code was present only if T1 and T2 involved mental rotation in the same direction, and not in case of opposite direction.

To our knowledge, this is the first illustration of modulation of parallel processing by the compatibility between two competing tasks. This result can not be explained by any dual-task model that explains interference by the relationship between the available processing capacity and task load, as the task load was identical for compatible and incompatible rotations. Instead the results argue for functional limitations to dual-task performance: the extent to which two tasks can be combined depends on the combination of tasks to be performed.

The modulation of the match effect by operation compatibility is reminiscent of the relationship between the match effect and task switching. There are illustrations of a match effect on trials that involve a task switch (Hommel, 1998; Lien, Schweickert, & Proctor, 2003), but Logan and Schulkind (2000) have shown a substantial reduction of the category match effect on switch relative to repetition trials.

Although modulation of the match effect by a task switch in itself underlines the importance of functional-capacity limitations in explaining the amount of parallel processing, it may not have the same origin as the asymmetry of match effects observed with compatible as compared to incompatible rotation. In the current study there was no need to switch the task set. Furthermore, rotating two stimuli in the same direction but over different angles did not remove the category match effect. Therefore, the tentative conclusion is that the absence of a match effect on incompatible trials can not be attributed to task set reconfiguration as it is commonly understood (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995), and should instead be attributed to the mere inability to simultaneously make a mental representation of two opposite directions of rotation.

As for our current experiment, the conclusions support the hypothesis that task content is a crucial factor to be considered when evaluating dual-task models. However, this first experiment is not yet conclusive in distinguishing between functional-limitation models, like the AEC model, the ECTVA model and the TEC model. In Experiment 2, S2 does not require mental rotation – it is only displayed in irrelevant circular motion. If we still observe modulation of the category match effect by the correspondence of rotation directions, it can not be attributed to the presence versus absence of a rotation reversal, as ECTVA would predict. Also, it can not be attributed to deferment of an error-prone mental rotation process, as AEC would predict. Hommel et al.'s (2001) TEC model, however, assumes that irrelevant and relevant features, both perceptual and mental share a common feature coding space, and predicts that the direction of irrelevant rotation of S2 will modulate parallel processing, as reflected in the match effect.

Experiment 2

While Experiment 1 required subjects to engage in *mental* rotation of S2 as a way to induce a rotation compatibility relation, Experiment 2 presents *physical* rotation as an irrelevant feature of S2. If the contribution of rotation compatibility to dual-task performance is limited to the compatibility of demanding operations, as predicted by structural capacity-limitation models, ECTVA or AEC models, Experiment 2 should not show a modulation of the category-match effect by the compatibility of rotations. If in contrast there are functional limitations, induced by conflict at the level of representing task features, Experiment 2 should show a larger category-match effect if the physical rotation of S2 is compatible with the mental rotation of S1.

To be able to distinguish between the different limitation-models, we adapted the first experiment as follows. We presented a tilted S1 in the centre of the screen, comparable to the first experiment. Participants were to judge whether it was presented in normal or mirror image. S2 however was an upright character, moving in circles around S1, either CW or CCW. Participants had to respond to the mirror/normal status of S1 and S2. Because S2 was presented in upright position, mental rotation was not necessary. In a category match, stimuli were either both mirror or both normal images, and mismatches were combinations of a mirror and a normal image stimulus. Rotation compatibility has a slightly different meaning in Experiment 2 than in Experiment 1. Rotations were compatible if the mental rotation required for bringing S1 to the upright position was in the same direction as the physical motion of S2 (i.e. both CW or both CCW).

Methods

All experimentation methods were the same as in Experiment 1, unless stated otherwise below.

Participants

Twenty students (four male) of Leiden University participated in this experiment that took ninety minutes. None of them had participated in Experiment 1. Three students indicated to be left-handed, the remaining were right-handed. All students had normal or corrected to normal eyesight. They received either twelve euros or course credits or a combination of these. One participant could not finish the experiment due to a technical error and the data were not used in data analysis. Two participants were excluded from the experiment, because the number of replications per cell was insufficient. Mean age of the participants was 22 years (*SD* = 3).

Stimuli

Two characters were presented within the rectangle, with a SOA separating them in time. S1 was always presented in the centre with S2 continuously moving in a circular course around S1. It took 1450 ms to complete one rotation of S2 and the movement was either CW or CCW. This made the speed of the movement 248°/sec, while the speed of the mental rotation for S1 was 337°/sec (as calculated by the difference in time between 120° and 60° rotation; this would calculate back to 1070 ms for one rotation). The movement of S2 was irrelevant for the response. The whole view within the limits of the rectangle was less than 5.6° horizontally and vertically.

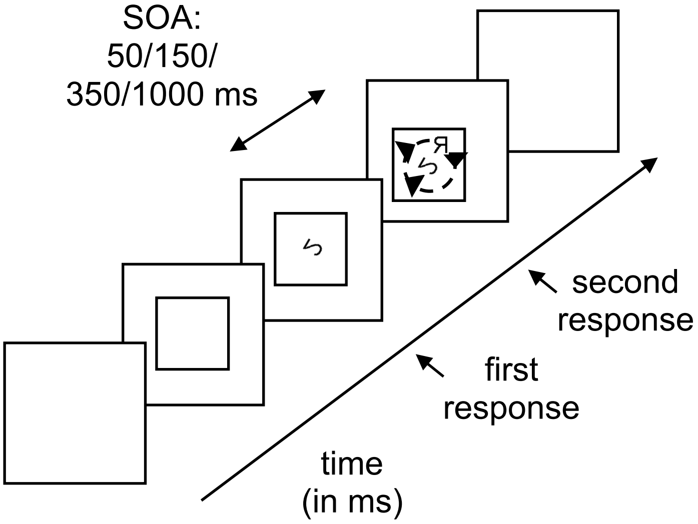

Figure 2.6. Sequence of events within one trial in Experiment 2: the rectangle serves as a fixation, in which S1 appears, and, after a short interval, S2. The arrows indicate circular motion and were not presented in the display

Design

Stimuli were presented in 50 blocks of 26 trials. S1 rotation angle, S1 tilting direction, S2 movement direction, S1 and S2 mirror vs. normal image, and SOA were all randomized. Because S2 was not tilted combinations of the angle combinations were 60°- 0° and 120°- 0° (0° was not presented for S1).

Procedure

Before the start of the experiment, participants received a written and a spoken instruction. Then more explanation was presented on the computer followed by a practice block containing 30 trials, after which the experimenter started the experimental blocks. In the trials, an RSI of 500 ms was used. For a sequence of events within one trial see Figure 2.6.

Results

All RT and PC results were analyzed in ANOVAs using a 2 × 2 × 2 × 4 design with the within-subjects factors rotation compatibility, category match, angle 1 and SOA, unless stated otherwise below. Table 2.5 and Table 2.6 show the mean performance and the ANOVA results are summarized in Table 2.7 and Table 2.8.

Table 2.5. Mean reaction times and percentages correct for Task 1 in Experiment 2

	RT1				PC1			
SOA (ms)	50	150	350	1000	50	150	350	1000
Angle 1								
60°	1364	1313	1294	1216	90.4	91.4	93.7	94.2
120°	1160	1132	1111	1074	94.8	95.2	94.7	95.5
Rotation compatible	1259	1224	1190	1145	92.7	92.9	94.7	95.6
Category match	1190	1138	1127	1133	94.6	94.1	95.0	95.7
Category mismatch	1329	1310	1253	1157	90.7	91.7	94.5	95.6
Rotation incompatible	1265	1221	1214	1144	92.5	93.6	93.7	94.0
Category match	1227	1178	1186	1144	93.4	95.0	92.8	94.3
Category mismatch	1303	1264	1242	1144	91.7	92.2	94.6	93.7

Table 2.6. Mean reaction times and percentages correct for Task 2 in Experiment 2

	RT1				PC1			
SOA (ms)	50	150	350	1000	50	150	350	1000
Angle 1								
60°	1622	1482	1291	878	96.2	97.1	97.2	98.5
120°	1425	1302	1118	811	96.6	96.8	97.7	98.5
Rotation compatible	1519	1394	1190	844	96.8	96.8	97.4	98.4
Category match	1414	1286	1099	816	97.5	96.7	96.7	98.8
Category mismatch	1623	1501	1281	873	96.2	97.0	98.2	97.9
Rotation incompatible	1529	1391	1219	845	95.9	97.1	97.5	98.7
Category match	1456	1321	1164	826	96.6	97.2	97.0	98.3
Category mismatch	1594	1460	1273	864	95.2	97.0	97.9	99.0

Table 2.7. Summaries for Analyses of Variance for performance on Experiment 2

	RT2					**PC2**			
Effect	df	MSE	F	p	part. η²	MSE	F	p	part. η²
Rotation compatibility (R)	1,16	8721	.60	.449	.036	36	.982	.337	.058
Category match (C)	1,16	101246	9.7	.007	.378	31	7.0	.018	.304
R × C	1,16	8348	15.2	<.001	.488	14	1.8	.196	.102
SOA (S)	3,48	111099	6.3	.013	.282	30	5.6	.005	.258
R × S	3,48	10409	.53	.665	.032	20	2.0	.141	.109
C × S	3,48	26692	6.1	.010	.277	28	4.0	.018	.200
R × C × S	3,48	10784	.68	.546	.040	29	.92	.420	.054
Angle 1 (A1)	1,16	12328	347.9	<.001	.956	65	14.4	.002	.473
R × A1	1,16	17505	.003	.956	.000	17	.47	.505	.028
C × A1	1,16	7240	4.1	.059	.206	30	1.8	.204	.099
R × C × A1	1,16	5280	.37	.550	.023	10	.043	.838	.003
S × A1	3,48	11417	2.7	.078	.144	26	4.6	.010	.223
R × S × A1	3,48	10819	.96	.406	.057	19	.44	.685	.027
C × S × A1	3,48	12584	3.1	.049	.160	24	.63	.565	.038
R × C × S × A1	3,48	8308	0.20	.877	.012	30	.61	.580	.037

Table 2.8. Summaries for Analyses of Variance for performance on Experiment 2

	RT2					PC2			
Effect	df	MSE	F	p	part. η²	MSE	F	p	part. η²
Rotation compatibility (R)	1,16	11926	.942	.347	.059	12	.11	.742	.007
Category match (C)	1,16	221047	10.5	.005	.412	18	.031	.863	.002
R × C	1,16	12885	9.5	.008	.387	7	.045	.835	.003
SOA (S)	3,48	65924	345.6	<.001	.958	12	10.4	<.001	.394
R × S	3,48	10159	.71	.530	.045	9	1.6	.226	.088
C × S	3,48	35850	6.0	.012	.287	11	4.4	.016	.215
R × C × S	3,48	12905	.71	.509	.045	15	.93	.411	.055
Angle 1 (A1)	1,16	13598	224.1	<.001	.937	9	.18	.678	.011
R × A1	1,16	17679	.50	.488	.033	12	.43	.520	.026
C × A1	1,16	6653	4.6	.048	.236	9	.27	.612	.016
R × C × A1	1,16	4708	.12	.730	.008	14	1.1	.320	.062
S × A1	3,48	12330	13.1	<.001	.466	8	.74	.505	.044
R × S × A1	3,48	11622	1.2	.308	.076	10	.52	.640	.032
C × S × A1	3,48	13553	4.2	.017	.217	12	.74	.493	.044
R × C × S × A1	3,48	11449	.79	.476	.050	10	3.1	.048	.160

RT1

Subjects were 85 ms faster on a category match relative to a mismatch, and 178 ms faster to 60° than to 120° tilted S1s. There was a gradual decline in RT1 as the SOA increased (1262, 1222, 1202, and 1145 ms respectively), but no main effect of rotation compatibility.

The most important interaction of rotation compatibility and category match was significant. The category-match effect was larger for compatible than for the incompatible rotation directions (116 ms vs. 54 ms, see Figure 2.7). Furthermore, the category-match effect was larger for short than for longer SOAs (111, 130, 91, 12 ms), and marginally larger for small than for larger angles (101 vs. 71 ms). A tendency for an interaction of angle 1 × SOA reflected that the effect of angle 1 decreased from 203 on short to 142 ms on long SOAs.

PC1

Subjects were 1.3% more accurate if categories matched as compared to mismatched, and 2.6% more accurate to 60° than to 120° tilted S1s. Accuracy increased with increasing SOA (92.6, 93.3, 94.2, and 94.8% respectively). With increasing SOAs, there was a decrease of the benefit of a category match from 2.8 to -0.3%, and a decrease of the angle 1 effect from 4.4% to 1.3%.

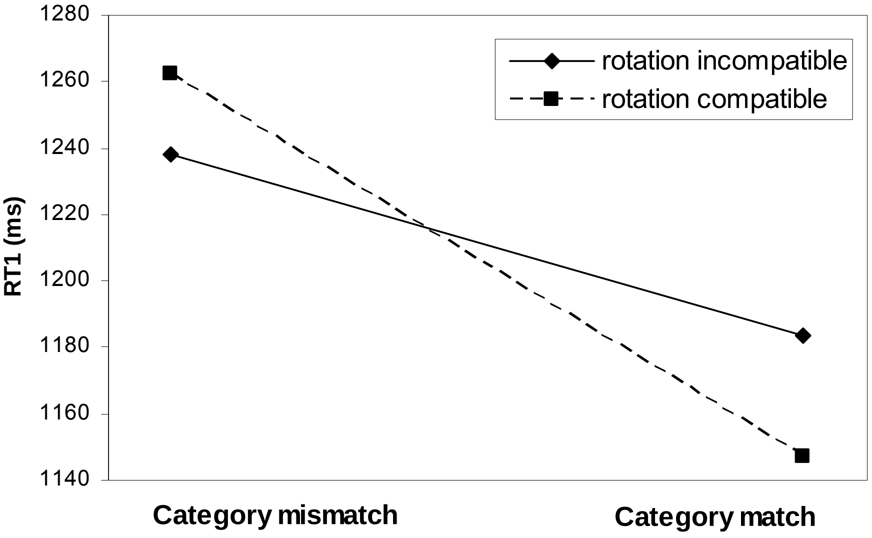

Figure 2.7. The interaction of rotation compatibility and category match on reaction time 1 in Experiment 2

RT2

The PRP effect was observed; RT2 decreased with increasing SOAs (1524, 1392, 1205, and 845 ms respectively). Subjects were 135 ms faster on a category match relative to a mismatch, and 154 ms faster to 60° than to 120° tilted S1s.

The category-match effect was modulated by rotation compatibility (165 ms for compatible and 104 ms incompatible rotations); by angle 1 (150 ms for small and 119 for larger angles) and by SOA (a decrease from 169 to 48). There was also a three-way interaction of category match × angle 1 × SOA, reflecting that the effect of angle 1 largely maintained its size on longer SOAs if categories mismatched, but decreased with SOA when they matched.

PC2

SOA showed the only significant main effect, with performance increasing with increasing SOA (96.4%, 97.0%, 97.5%, and 98.5% respectively). There was an interaction of category match × SOA, showing that the category-match effect was positive only on the shortest SOA. A four-way interaction of rotation compatibility × category match × angle 1 × SOA reflected no meaningful pattern.

Discussion

In this second experiment, we investigated the influence of a non-demanding and irrelevant process representation of S2 features on RT1, as reflected in the category-match effect. To that end, we varied the circular movement of S2, which itself was presented in normal or mirror image, but always in an upright position.

RT1 and RT2 both decreased with SOA, indicating mutual limiting effects between T1 and T2 processes. The decrease of the angle 1 effect from RT1 to RT2 suggests that T2 processes were not entirely deferred until rotation of S1 had finished. The extent to which T2 processes continued is reflected in the category-match effect.

Just as in Experiment 1, RT1 was relatively fast if the response categories for T1 and T2 matched, suggesting that R2 activation started before R1 was selected. It also shows that there is crosstalk between T1 and T2 processes that causes a relative benefit for matching response categories: parallel processing is facilitated and the dual-task interference is reduced.

As predicted by some functional-limitation models (e.g., Hommel et al., 2001), rotation compatibility modulated the size of the category-match effect. When the rotation directions were compatible as compared to incompatible, the category-match effect was more than twice as large. Because the rotation of S2 was irrelevant and did not contribute to the complexity of the task, it can not have been involved in a demanding process of T2. Because of the random presentation of the trials, it was also not possible and of no use to predict the mental rotation direction of T1 from the rotating direction of T2. The fact that compatibility nonetheless modulated the category-match effect means that incompatible rotations either slowed down S1 rotation, or led to suppression of T2 processes, or both. Because rotation compatibility did not interact with angle 1 on RT1, there did not seem to be a modulation of S1 rotation. Therefore, the compatibility effect must be attributed to changes in T2 processes, which in turn affected the size of the category-match effect.

General Discussion

Summary of the results

In two experiments we have shown that while subjects perform on a primary mental rotation task, they can already determine and activate the correct response category for a second task. In both experiments T1 was to determine the mirror/normal status of a tilted character. In Experiment 1, T2 required mental rotation like T1, while in Experiment 2, S2 was always upright and therefore required no mental rotation, but the upright stimulus was moving along a task-irrelevant circular path. In both experiments, the match between the response categories of both tasks affected RT1. As explained by Logan and Schulkind (2000), this category-match effect is a sign that two tasks were performed in parallel.

Moreover, the amount of parallel processing in both experiments was modulated by the compatibility of mental rotation with concurrent events. In Experiment 1, the compatibility between the directions in which stimuli required mental rotation affected the category-match effect. In Experiment 2 the match effect varied as a function of the compatibility between the required mental rotation for S1 and the irrelevant rotation of S2. These results point out that dual-task limitations can not be explained exclusively in terms of structural capacity limitations, but that also the relationship between tasks influences the amount of parallel processing. Importantly, these limitations are not exclusively evoked by demanding processes, but can also arise if irrelevant activity is in conflict with a mental operation. These inferences will now be discussed stepwise.

Is mental rotation a bottleneck process?

Previous studies have shown that the task to decide whether a tilted stimulus is presented in normal or mirror image first requires mental rotation of the stimulus to its upright position (Corballis, 1986). Mental rotation imposes a strong burden on the cognitive system and thereby limits concurrent processes of the same (Band & Miller, 1997) or other tasks (Ruthruff et al., 1995). Some researchers assert that mental rotation has bottleneck properties in the sense that no other central processes can take place simultaneously with mental rotation (Pashler, 2000). Consistent with this assertion, the angle 1 effect in Experiment 1 was equally large on RT1 and RT2, which implies that at least some T2 processes waited for mental rotation of S1 to finish. In Experiment 2, the effect size of angle 1 was smaller on RT2 than on RT1. The combination of the two experiments might be taken to suggest that during the delay imposed by mental rotation of S1, RT2 could not benefit from starting mental rotation of S2, whereas other processes such as the mirror/normal judgment of an upright stimulus could make progress. Then, at first glance mental rotation seems to have bottleneck properties. However, locus of slack studies have shown that angle effects of T2 are sometimes attenuated on short SOAs (Van Selst & Jolicœur, 1994). In our experiment, the effect of angle 2 on RT2 was hardly modified at longer SOAs. This suggests that during the phase of temporal overlap between tasks, mental rotation of S2 did not continue before critical processes of T1 had been completed. Actually, this effect can be explained both in structural and in functional terms.

Parallel mental rotation

In both experiments RT1 decreased with increasing SOA. Moreover, the current study strengthens the support in favour of parallel execution of demanding processes such as mental rotation by showing that R1 was faster for matching than for mismatching response categories of T1 and T2. This effect at the least implies that T2 processes lead to a preliminary preference for the correct response category before the response category of T1 has been selected.

How certain is it that mental rotation, rather than another pair of processes was time sharing? Given that mental rotation is a process of long duration (up to 350 ms for 120° angles) it is a priori difficult to find an alternative explanation. The category-match effect can only arise if mental rotation has at least produced preliminary support for R2 before R1 is selected. First, one might argue that subjects were able to categorize S2 without mental rotation, and that the category-match effect relied entirely on such direct translation without mental rotation. However, this explanation can easily be refuted because the occurrence of the category-match effect in Experiment 1 was modulated by rotation compatibility and thus clearly depends on rotation.

Three other alternatives need to be excluded. Mental rotation of S1 and S2 might have been performed serially, yet before R1 selection. Apart from the fact that this would result in very long RT1s, it would be consistent with the occurrence of the category-match effect. If subjects interrupted T1 processes in favor of T2 processes, the category-match effect would not be a sign of parallel processing. Instead, it would be a forward priming effect from processing S2 to subsequent processing of S1. Furthermore, subjects may have switched back and forth between mental rotation processes. Although switching introduces new problems such as switch costs and higher requirements for keeping task performance separated, it would be a way to complete both tasks without sharing capacity. Finally, on a subset of trials, subjects might reverse the order of tasks. Given that only trials with responses in the correct order were analyzed, only the reversal of initial processes would go unnoticed and not the actual reversal of responses. The problem with these three explanations is that they all predict that RT1 increases with increasing SOA, while the opposite pattern was found. In conclusion, there is strong evidence in favour of parallel mental rotation for two tasks.

Modulation of the category-match effect

To explain category-match effects in a dual task, Hommel (1998) distinguished between two phases of response selection. An initial phase can activate one or more responses associated with the stimulus, but this activation does not necessarily result in an overt response. In a later phase, a rule-based response decision is made. Hommel argued that R2 activation can start before the R1 decision is made, although the R2 decision may need to wait until the R1 decision is finished. The current category-match effects are only partially consistent with this distinction. As the determination of response categories (mirror/normal) was contingent on mental rotation for both tasks of Experiment 1, the category-match effect implies that it was mental rotation that produced preliminary activation. In other words, R2 activation entailed more than a direct S-R association, it involved a process that is generally agreed to be a heavy burden operation.

The modulation of category-match effects by rotation compatibility suggests that parallel rotation is limited by the synchrony of the directions of rotation. On incompatible mental rotations, there was no significant category-match effect. It is clear that these limitations can not be attributed to task load, as even Experiment 2 showed a reduction of the category-match effect with incompatible rotation when S2 rotation was irrelevant. Thus, the reduction is not caused by an inherent limitation to performing incompatible heavy-burden operations. Instead, the incompatibility of representations seems to be the key issue.

Meyer and Kieras' (1997a; 1997b; 1999) AEC models could be designed to defer processing S2 if its rotation poses a risk for reaching the goal to respond to S1, but this deferment would be done in anticipation of a task, not in response to the risk of errors encountered from trial to trial. Other models do assume that executive control can be applied to adjust the processing strategy immediately upon the detection of conflicting response tendencies (e.g., Miller & Cohen, 2001; Norman & Shallice, 1986; Ridderinkhof, 2002), but we are not aware of a model that would explicitly predict a shift from parallel to serial processing. The model that comes closest is that of Luria and Meiran (2005), who have argued that if control requirements increase in a PRP task, subjects may switch from parallel to serial processing. However, this idea applied to task switches versus repetitions. To what extent could this idea be extended to switches in rotation direction? Before we can answer this, we need to have a model of how task switches modulate the category-match effect.

Logan and Gordon’s (2001) ECTVA model suggests that crosstalk can be modulated by the overlap between task sets. Priming of S2 onto S1 could occur if mental rotation in the direction of T1 activated meaningful response categories, which was only the case if mental rotation in the direction of T1 brought S2 to the upright position. While ECTVA can explain the modulation of the category-match effect in Experiment 1, the same explanation does not hold for Experiment 2, since the mirror-normal discrimination of S2 did not require mental rotation. The modulation of the category-match effect by an irrelevant stimulus feature can therefore not be attributed to the involvement of task switching.

The conjecture that we believe is best capable of explaining the pivotal interaction of rotation compatibility and category match is in terms of the effects of crosstalk in a unified encoding environment. Both relevant and irrelevant features involved in the two tasks were activated, and in line with TEC (Hommel et al., 2001), stimulus features (the irrelevant rotation of S2 in Experiment 2) interfered with the representations involved in the mental rotation process of T1. The performance costs of conflict caused by the activation of opposite directions of rotation may be attributed to mechanisms such as reciprocal inhibition (cf. Coles, Gratton, Bashore, Eriksen, & Donchin, 1985), slower accumulation of support for a response (Ratcliff, 1988), or even active inhibitory control (Ridderinkhof, 2002). A distinction between these mechanisms, however, is beyond the scope of this article.

Task content versus Task load

In this study we have distinguished between structural-limitation models and functional-limitation models of dual-task performance. We have demonstrated the importance of task content (independent of task load) in causing dual-task interference and limiting parallel processing. Yet, this study should not be interpreted as a plea against the contribution of task load. Many results in the literature can not be explained without referring to task load, and the effect of S2 angle on RT1 in Experiment 1, for example, shows that an increased task load in a task indeed slows down the competing task. The message of the current study, however, is that task load can not explain all dual-task processing limitations.

One of the most counterintuitive findings was the fact that a non-demanding perceptual event, irrelevant rotation of S2, interfered with mental rotation. This clearly validates the use of task content as an indispensable part of the explanation of when dual-task processing is facilitated or impeded. Moreover, it exposes a blind spot in current models of dual-task performance. Thus far, capacity models were all focused on the contribution of demanding processes to the possibility to perform on two tasks simultaneously. The idea that non-demanding or even passive processes such as observing a rotating character can affect dual-task performance calls for more attention to interactions between operations and representations in working memory.

We acknowledge that some authors have investigated interactions between operations, between operations and working memory representations (e.g., Oberauer & Göthe, 2006). However, these accounts apply to the effect that one process has on the other, not on the modulating effect of compatibility between concurrent processes on parallel processing. It is this contribution that we find too important to dismiss, as we have demonstrated by both experiments.

Whether parallel processing stands a better chance when tasks do or when they do not overlap in perceptual-motor requirements is still a matter of debate. Pashler (1994) recommended for PRP experiments to combine tasks that shared no requirements except for the need to make SR-translations. This has led to a tradition in which combinations such as a visual-manual and an auditory-vocal task are used. Indeed, Meyer and Kieras (1999; see also Schumacher et al., 2001) argued that the absence of perceptual and motor overlap between tasks is one of the preconditions for obtaining perfect time sharing. In contrast, Logan and Gordon’s (2001) ECTVA model assumes that dual-task interference increases as a function of the number of adjustments to the task set that need to be made. This would predict more parallel processing if tasks show less overlap. Consistent with this assertion, studies that have demonstrated parallel processing with the category match effect all (by definition) made use of task overlap, and the category match effect is reduced by the need to switch between tasks.

Relation to other dual-task compatibility studies

The current study demonstrated the importance of between-task compatibility for the ability to combine tasks. Previous dual-task studies have emphasized other aspects of task combinations that deserve to be mentioned here. In particular, several models assume that processing capacity is modality-specific (Wickens, 1984). For example, it is better possible to combine a visuo-spatial with an auditory-vocal task than to combine two visuo-spatial tasks (Baddeley, 1986). Likewise, Wickens (1984) argued for separate resources for perceptual channels and effector channels that limit the ability to combine similar tasks.

It is important to emphasize that modality-specific limitations to dual-task performance are imposed by the task load rather than the content of the constituent processes. While two tasks that share modality-specific resources are *resource incompatible* (the two tasks can not be combined due to resource limitations), they may well be *content compatible* (the two tasks can be combined without operations or representations affecting each other negatively). Conversely, the current Experiment 2 showed that tasks that do not both impose a heavy task load may be resource compatible, but content incompatible.

The compatibility between concurrent task operations can be approached with the same theoretical framework that is also used in explaining compatibility effects in single tasks (cf., Kornblum, et al., 1990; Kornblum & Lee, 1995), under the assumption that concurrent processes produce crosstalk. The important addition made in the current study is that these compatibility relations are not restricted to feature representations of stimuli and responses, but also apply to mental operations such as mental rotation.

We argue that capacity limitations alone, whether in single or in multiple modules, are insufficient to explain the current results and that the relevance of task content in this regard is neglected in the literature on dual-task performance. Two studies have previously shown a compatibility effect of perceived rotation on sequential mental rotation. Corballis and McLaren (1982) have shown that after the presentation of a rotating disc, the rotation after-effect influenced the direction in which subjects performed mental rotation of stimuli that were almost upside down. Heil, Bajrić, Rosler and Hennighausen (1997) showed that this perceptual after-effect also affected the speed of mental rotation. Recently, a third study showed after-effects that transfer between operations. Graf, Kaping and Bulthoff (2005) demonstrated a beneficial effect on the accuracy of naming a tilted object that was masked after a brief presentation if it immediately followed a prime stimulus that required mental rotation in the same direction. Nonetheless, these studies give no hint about the effect that the compatibility of rotation would have on concurrent processing. An interesting exception in the current context is a study by Wohlschläger (2001; see also Wohlschläger & Wohlschläger, 1998), who instructed subjects to plan a hand movement, but to execute it only after a mental rotation task was completed. Mental rotation was faster if the concurrent tasks involved movement in the same relative to opposite direction. The author concluded that the representation of the intention for a hand movement interfered with rotation. This is consistent with our assertion that dual-task interference arises as a result of competition between task content; not only between operations, but also between a non-demanding mental representation and a cognitive operation.

Closing remarks

It is an interesting question for future research whether the rotation compatibility effects on parallel processing that we demonstrated can be generalized to operations other than mental rotation and events other than perceived rotation. There are several interesting ways to follow up on the current study. There is a rich tradition of manipulating spatial operations other than rotation, and many of these are amenable to be implemented in a dual-task setting. Also, combinations of mathematic and mnemonic tasks can be designed to use the same instruction and task set, but operations that are either compatible or incompatible between concurrent tasks. We predict that, just as in the current study, it is easier to perform tasks in parallel if they make use of compatible as compared to incompatible operations. As the current study has shown, the use of the category match effect can be a powerful tool for demonstrating changes in parallel processing.

Chapter 3

What do Psychological Refractory Period and Attentional Blink have in Common?

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Abstract

The Attentional Blink (AB) paradigm and Psychological Refractory Period (PRP) paradigm are both dual task paradigms in which performance on the second task is impaired by processing limitations. We investigated the relationship between individual AB and PRP effect sizes and tested whether the two effects share predictors. AB effect sizes were positively correlated with PRP effect sizes, suggesting a common functional basis. Consistent with previous research, we found that AB effect magnitudes are predicted by working memory (WM) operation span size (as measured by OSPAN) but not by fluid intelligence (as measured by Raven's SPM) and were able to extend this finding to PRP effects. However, the connection between PRP and WM operation span was weaker than that between AB and WM, suggesting that PRP tasks are less dependent on WM.

Introduction

There are two frequently used paradigms that measure how multiple stimuli are processed when presented in short succession: the Attentional Blink (AB) paradigm and the Psychological Refractory Period (PRP) paradigm. In the AB (Raymond, Shapiro, & Arnell, 1992), there is a rapid serial visual presentation (RSVP) of around twenty distractors, mixed with two or more targets that require unspeeded report at the end of each trial. The temporal difference between the two targets is varied by the number of distractors in between, and is indicated by the so-called lag, i.e., the serial position of the second target (T2) relative to the first (T1). Whereas T1 accuracy is generally high, report on T2 depends on the lag: long lags show highly accurate report, while short lags (typically 100-500 ms post-T1) show decreased accuracy.

In the PRP paradigm (e.g., Pashler, 1994; Welford, 1952), two stimuli are presented in close temporal succession. The variable time between the onset of the first stimulus (S1) and of the second (S2) is called the stimulus onset asynchrony (SOA). Typically, when the temporal overlap increases (i.e., SOA decreases) the reaction time to S2 (RT2) increases. This RT2 effect reflects a delay that S1 processing imposes on S2 processing. If SOA is long enough, however, RT2 decreases and reaches an asymptotic level.

Thus, in both paradigms, participants show impaired performance on the second task resulting from the requirement to process two relevant stimuli in short succession. The main purpose of this study was to investigate whether the sources of the effects observed in these paradigms overlap.

Shared vs. unique mechanisms

Jolicœur (1999) has investigated the relation between AB and PRP and presented a Central Interference Theory to explain the results of both paradigms (see also Jolicœur & Dell'Acqua, 1999; Pashler, 1994). This theory is built on the assumption that both short-term consolidation and response selection make use of a capacity-limited central mechanism. In non-speeded AB tasks, consolidation for T2 can only be deferred by consolidation for T1, because response selection can be postponed until after the end of the trial. However, in an AB task with speeded R1, response selection for T1 defers consolidation for T2. This in turn would make it harder to report T2 accurately over time, because the appearance of the mask would impair ongoing bottom-up stimulation, which would result in decay of the target (Coltheart, 1980) or interference by the mask (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; see also Jolicœur, 1999). Consistent with this model, effects on R2 selection induced by a variable number of response alternatives enhanced the AB in the speeded, but not in the nonspeeded version.

In the PRP task, response selection processes of T2 are deferred by consolidation of T1, as demonstrated by Jolicœur and Dell'Acqua (1999), or by response selection for T1 (Pashler, 1994). Jolicœur and Dell'Acqua also demonstrated that trials with a long RT1, presumably involving prolonged response selection, interfered more with T2 consolidation, as demonstrated by a reduced accuracy of reporting a masked T2. In sum, these studies suggest AB and PRP have a shared locus of interference.

Other research however, suggested that AB and PRP have a different locus of interference. Wong (2002) conducted an AB to compare dual-task delays in both the PRP and the AB. First, he added a speeded response for T2 in the AB to obtain RTs. Additionally, T2 intensity was varied to investigate whether the impairment in the AB was caused by a similar bottleneck mechanism that causes the PRP effect. Previous PRP research showed an underadditive effect of perceptual processes like processing intensity and SOA on RT (e.g., Jentzsch, Leuthold, & Ulrich, 2007; McCann & Johnston, 1992). Results for the AB with speeded R2 showed an underadditive interaction between T2 intensity and lag on RT and an overadditive effect for the same interaction on accuracy. The RT interaction effect suggests that AB-limitations come from central capacity limitations because perceptual processing precedes central capacity-limited processing. The accuracy effect, however, suggests that AB-limitations come from a limitation in visual processing. The dissociation between RT and accuracy results suggests that there are two different sources of interference in the AB, of which the RT effect resembles the interference shared with the PRP.

Additionally, some studies have investigated the relation between the AB and PRP electrophysiologically (e.g., Vogel & Luck, 2002; Arnell, Helion, Hurdelbrink, & Pasieka, 2004). One event-related potential component, the P3, reflects completion of stimulus identification or categorization (Donchin, 1981). Arnell et al. (2004) used P3 latency in two experiments, of which the first experiment entailed an AB with a masked, unspeeded R1 and a speeded R2. The second experiment was a PRP paradigm, similar to the first experiment except that T1 was not masked and a speeded response was required. Arnell et al. (2004) measured the P3 latency in both paradigms to investigate whether the delay occurred at the same stage or at a different stage. If the P3 latency was proportional to the SOA and RT delay then the dual-task delay occurred before stimulus identification. Alternatively, when the delay of the P3 was not related to the size of the SOA then the dual-task delay occurred after stimulus identification. Results showed a significant relation between P3 latency and response slowing in the AB, but not in the PRP. This is an indication that the main delay of the second response arose before stimulus categorization for the AB but after stimulus categorization for the PRP, which in turn suggests a different cause of interference for the two paradigms. To conclude, the available research provides evidence for both shared and unique sources of dual-task interference in the PRP and AB paradigm.

Modality specific vs. modality independent

Arnell and Duncan (2002) investigated whether the source of interference is shared between paradigms by comparing the interference in bimodal and unimodal dual tasks. Bimodal tasks use two different sensory processing routes (e.g., visual – auditory) while unimodal tasks use one single processing route (e.g., visual-visual). Arnell and Duncan (2002) assumed a single bottleneck when the interference effects were limited to the unimodal condition, while an additional interference effect for bimodal tasks would imply the existence of multiple bottlenecks. In their first dual-task experiment, they randomly presented unimodal and bimodal trials in an unspeeded task. For both tasks, modality (auditory or visual) and SOA were varied. Results showed T2 performance impairments on unimodal trials as well as in bimodal trials. The interference was larger in the unimodal trials, which is a result that is in line with a unimodal bottleneck. Experiment 2 was similar to the first experiment, but now a speeded dual task was used. Task load was varied in the auditory task by having participants make either a pitch or identity judgment (easy) or both (difficult). Again, results showed T2 impairment in the unimodal as well as in the bimodal tasks, with the largest impairment for the unimodal condition. The use of a higher task load in the second experiment for the auditory task caused increased T2 impairment. Arnell and Duncan (2002) concluded that the existence of interference on both bimodal and unimodal trials excludes the possibility of a sole bottleneck. A model with two forms of capacity limitation seems most probable: an early limitation at stimulus encoding and a later limitation at response selection (Pashler, 1989) or consolidation (Jolicœur, 1999).

Current experiment

In our experiment we set out to examine the relative contributions of unique and shared sources of interference by considering individual differences in the sizes of AB and PRP effects. If, and to the degree that these effects are functionally related, they should not only show similar performance characteristics and be affected by the same variables, but they should also covary in size across participants. In other words, people who show large PRP effects should also show large AB effects. Accordingly, we acquired PRP- and AB-measures from the same population and tested whether and to which degree these measures would be related to each other. Additionally, we tested whether the AB- and PRP effects could be predicted (and, thus, probably explained) by WM operation span (as measured in the OSPAN task) and/or intelligence (as measured by the Raven's Standard Progressive Matrices; SPM). The selection of these predictors was inspired by a recent study of Colzato and colleagues (Colzato, Spapé, Pannebakker, & Hommel, 2007), who demonstrated that the AB magnitude could be predicted from WM operation span but not IQ: Participants with higher WM operation span showed a smaller impairment for the AB, independently of IQ. Note that it is important to dissociate the effects of IQ and WM operation span as these two represent overlapping but non-identical constructs (Conway, Kane, & Engle, 2003; Süβ, Oberauer, Wittmann, Wilhelm, & Schulze, 2002).

The findings of Colzato et al (2007) were confirmed by Arnell, Stokes, MacClean, and Gicante (in press). They extended the Colzato et al. study by adding two more WM tasks to verify that it is solely the executive control component of WM (as measured by the OSPAN) but not the storage component of WM that predicts the AB magnitude: a forward digit span to measure the storage component and a backward digit span to measure the combined effects of storage and executive control. Results showed that AB magnitude and WM operation span (as a measure of high executive control) were significantly correlated with SPM, even when forward digit span and backward digit span were partialled out. Arnell et al. (in press) argue that it is the greater executive control in people with a high WM operation span that makes it easier for them to block out distractors in the RSVP stream of the AB.

The replication of Colzato et al.'s (2007) findings by Arnell et al. (in press) is particularly important in the face of Martens and Johnson's (2009) failure to find a correlation between AB magnitude and WM operation span. Instead of the OSPAN used by Colzato et al., Martens and Johnson used a symmetry span task, a reading span task, a matrix span task and a letter span task to measure WM operation span. These tasks all tap into the same WM construct (Kane et al., 2004), but given its lower storage requirements the OSPAN is likely to provide a purer measure of WM's executive control component. Indeed, Arnell et al., found that a task that requires storage but little executive control (i.e., backward digit span) does not correlate with AB magnitude while the OSPAN does.

In sum, we were interested to see whether performance in PRP and AB tasks would correlate across participants, and whether it would be modulated by the same types of individual capacity measures. In particular, we considered three hypotheses that a common-mechanism approach would suggest. First, there should be a positive correlation between AB magnitude and PRP effect (H1): If these two effects reflect the same mechanism, people with a pronounced PRP effect should also show a strong AB magnitude. Second, there should not only be a correlation between AB magnitude and WM operation span (a prediction that was rather trivial, given that our subjects partially overlapped with those of Colzato et al., 2007) but also a correlation between PRP effect and WM operation span (H2). Third, AB effect, PRP effect and their possible modulation by WM operation span should be related to intelligence in comparable ways (H3).

Methods

Participants

Twenty-nine students (3 men) between 18 and 30 years old participated in this experiment for course credit or monetary compensation. Twenty-two of these students were already tested on IQ, OSPAN and AB in the Colzato et al. (2007) study. The OSPAN varied between 34 and 56 (maximum points: 60; median: 45) and the IQ ranged from 100 to 140 (median: 115). All students had normal or corrected to normal eyesight, and were not familiar with the purpose of this experiment.

Apparatus

The PRP task was conducted on an ACPI uniprocessor computer with a 19'' CRT screen refreshing at 120 Hz using E-Prime for stimulus control. The remaining tasks were conducted on a Pentium III computer with a 17'' CRT screen refreshing at 100 Hz running under E-Prime with a viewing distance of approximately 50 cm. The resolution of the monitor in the AB task was 800 by 600 pixels in 16 bit color.

Procedure and design

Four tasks were conducted: the AB paradigm to measure the attentional impairment in reporting the second of two targets in terms of AB magnitude; the PRP paradigm to measure the dual-task delay in terms of the PRP effect; the operation span task (OSPAN) to measure WM capacity, and the Raven test (Raven, Court, & Raven, 1988) to measure fluid intelligence. Participants always started with the RSVP task followed by the OSPAN and Raven sessions counterbalanced between subjects. For the 22 participants tested in the Colzato et al. (2007) study, the PRP paradigm was conducted in a separate, later session which was taken with an approximate six months delay from the first session. Note that, if anything, this delay between the PRP task and the other tasks makes the test more conservative. The remaining seven participants were tested in two sessions with an approximate delay of a month. All correlations were tested two-sided with a significance level of $p < .05$.

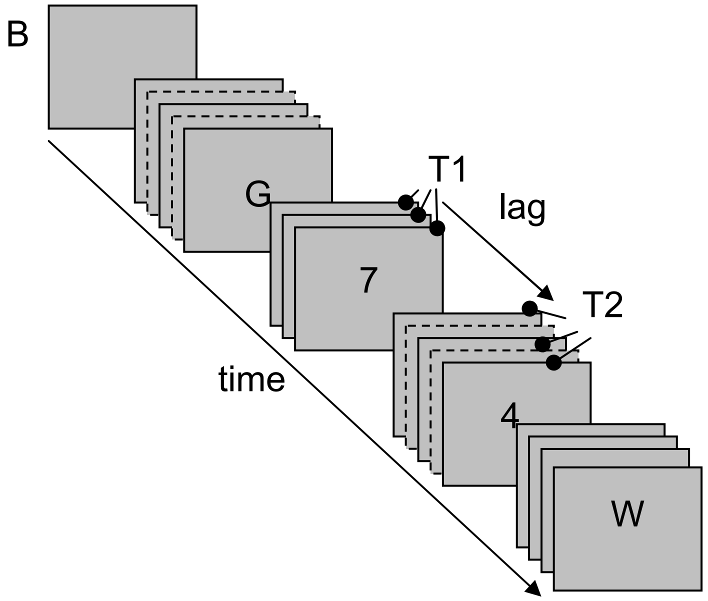

Figure 3.1. Events in the RSVP trial. A new display appeared every 80 ms. The two targets (T1, T2) – digits amongst letters–were separated by either zero, two, four or seven nontarget displays, defining the lag. The first digit was either presented between position 7, 8 and 9 of the visual stream. The possible positions of T1 and T2 are indicated in the figure.

In the AB task, two targets, T1 and T2, were presented in an RSVP (rapid serial visual presentation) stream of distractor letters. The two targets were digits that randomly varied between 1 and 9. The distractor letters were selected randomly without replacement from the alphabet. The targets required unspeeded report at the end of each trial; order was not considered in calculating accuracy. Figure 3.1 shows the sequence of events in a trial. The fixation mark (‘+’), the distractor, and the targets always appeared in the centre of the screen in black on a grey background. Participants first received written instructions, after which they practiced for 24 trials. Only when participants obtained a percentage correct of more than 50%, they were allowed to continue. Otherwise they had to perform another practice session. The trial started with a fixation point shown for 2000 ms, followed by a blank interval of 250 ms. Then, the RSVP started, consisting of 20 items and alternating a 40 ms item presentation with a 40 ms inter-stimulus interval.

The experiment contained one block of 360 trials (3 locations of T1 x 4 lags x 30 repetitions) and took 30 minutes. To reduce the predictability of target onset, T1 was presented randomly at the 7th, 8th, or 9th position in the RSVP. T2 followed immediately (lag 1), or after another 2, 4, or 7 distractors (lag 3, 5, and 8 respectively).

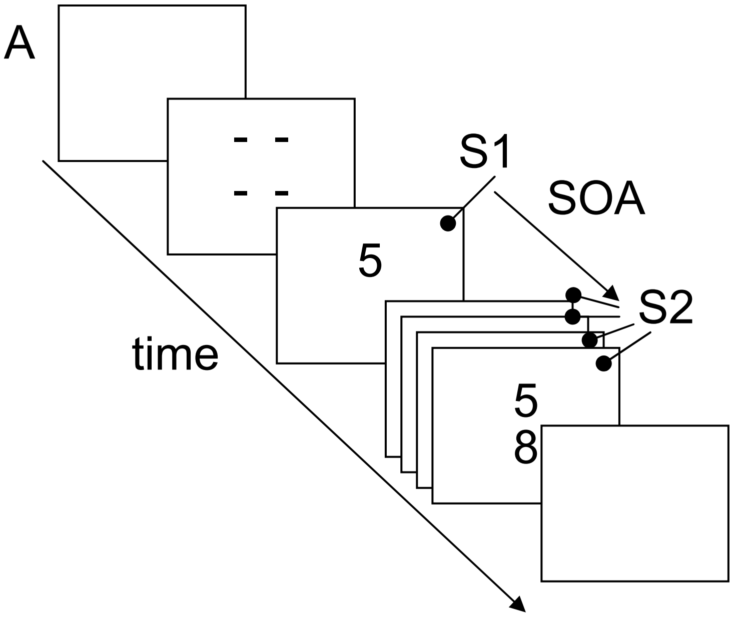

Figure 3.2. Sequence of events within one trial in the PRP trial: the 4 '-' markers serve as a fixation, in which S1 appears above the centre of the screen, and after a variable SOA S2 appears below the centre of the screen. The possible positions of S1 and S2 are indicated in the figure.

In the PRP task, two stimuli were presented with an SOA of 0, 100, 300 and 900 ms (see Figure 3.2). Both stimuli were digits (1-9) that were to be judged as odd or even. S1 appeared above the centre of the screen and called for a response with the index or middle finger of the left hand. S2 appeared below the centre of the screen and called for a response with the index or middle finger of the right hand. The mapping of odd/even responses onto the index/middle fingers was balanced across participants. Participants received instructions after which they practiced for 24 trials during which feedback was given after each trial. Then, participants conducted the experiment in four blocks of 80 trials which took approximately 20 min. A trial started with a fixation for 500 ms followed by the presentation of S1 above the centre of the screen. After the variable SOA, S2 appeared below the centre of the screen for 1000 ms: then both S1 and S2 disappeared. 3500 ms later the next trial was initiated and the time to respond had passed. At the end of each block, participants were given feedback on their performance by presenting their average RT and accuracy for the two tasks. We excluded all trials in which R2 preceded R1 (SOA + RT2) – RT1 > 0).

The OSPAN (operation word span) task (adapted from Turner and Engle, 1989) was used to measure individual WM capacity. In this task, a series of 2-6 calculation-word pairs is presented in the centre of the screen, e.g., “is (8 / 2) + 5 = 9 ? train”. Participants were to read the sum out loud, give the answer to the calculation and then read the word out loud while remembering it for recall (in correct order) at the end of the trial. There were three practice trials after which 15 experimental trials were presented: 3 trials of each combination of calculation-word combinations (2-6). The OSPAN took approximately 15 min to conduct. Trial order, calculation and words were completely randomized. In total, there were 60 words to be remembered correctly which gave a maximum of 60 points; one point per correctly remembered word. The OSPAN task measures a combination of storage and executive-control capacity (Engle, Kane, & Tuholski, 1999), with an emphasis on the latter.

The Raven’s Standard Progressive Matrices (SPM) test was used to measure the individual IQs. The SPM takes about 30 min and is a reasoning-based intelligence test. In this test, the participants were shown 60 items. Each item of the test consisted of a pattern or sequence of a diagrammatic puzzle with one piece missing, and participants had to complete the pattern or sequence by choosing the correct missing piece from a list of options. The items become increasingly difficult as the participant proceeds through the test. The SPM is used to assess Spearman's g factor and fluid intelligence in particular (Raven et al., 1988). Additionally, it measures to what extent participants are able to create perceptual relations and to reason by analogy independent of language and formal schooling.

Results

ANOVAs

Data from the AB show a typical effect for T1 and T2. If tested in a repeated measures analysis of variance (ANOVA) with lag as a within-subjects factor, T1 performance yielded a significant effect, *F* (3,84) = 90.3, *p* < .001. Figure 3.3 shows that this effect is largely due to a decreased performance on lag 1 compared to the other lags. This decreased performance on lag 1 has been shown before in AB paradigms with similar targets; it is likely to reflect competition between T1 and T2 (Akyürek & Hommel, 2005; Potter, Staub, & O’Conner, 2002). T2 performance (T2|T1; T2 performance for correct T1s) also showed a significant effect of lag, *F* (3,84) =

40.4, *p* < .001. The paired samples t-test for T2 investigating the decrease in performance from lag 1 to lag 3 was significant, *t*(28) = 7.7, *p* < .001. The recovery from lag 3 to lag 8, although not complete, was also significant, *t*(28) = 2.9, *p* = .007. This traditional AB pattern has been reported before by many others (e.g., Chun & Potter, 1995; Shapiro, Raymond, & Arnell, 1994).

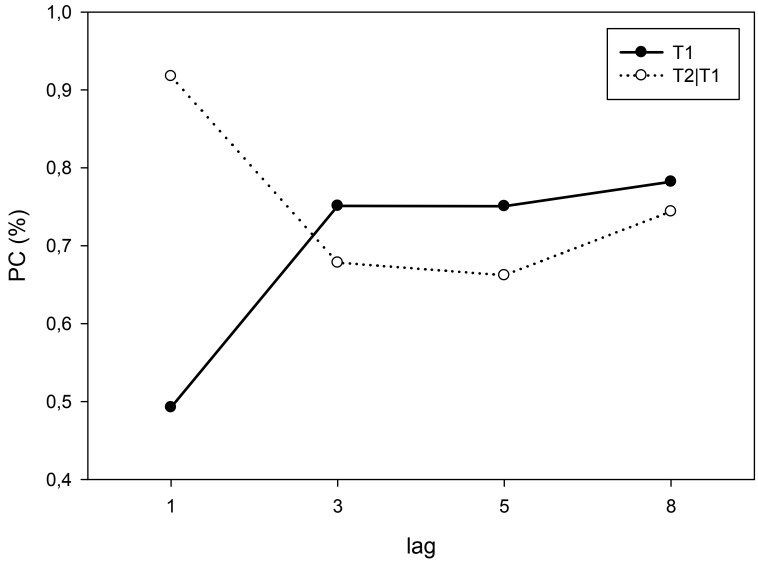

Figure 3.3. Performance results (%) per lag (lag 1, 3, 5, and 8) for T1 and T2

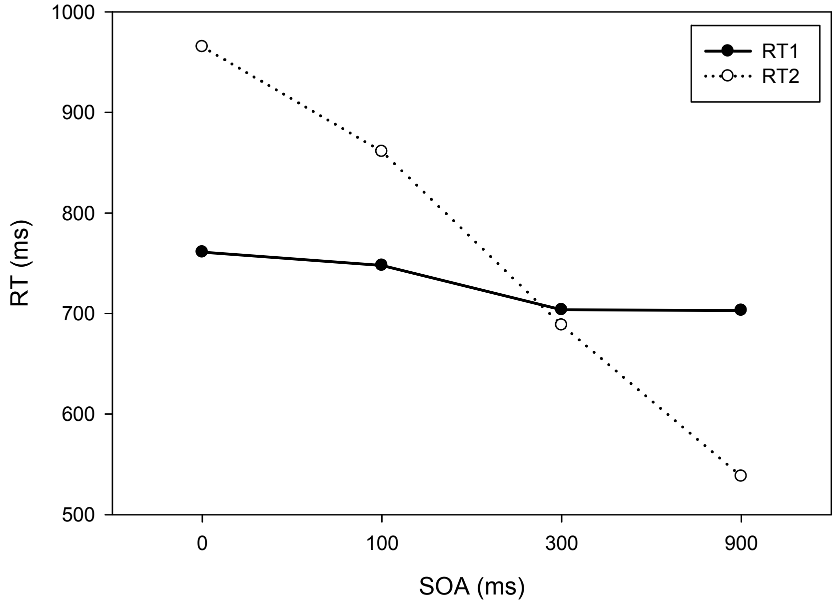

Figure 3.4. RT1 and RT2 results for the PRP paradigm over the different SOAs

Data from the PRP paradigm were analyzed in a repeated measures ANOVA with SOA as within-subjects factor. Results showed a significant main effect of SOA on RT1, *F*(3,84) = 7.4, *p* = .005: RT1 increased as SOA decreased (see Figure 3.4). Contrasts showed that the only significant difference is between SOA = 100 ms and SOA = 300 ms: this difference is 44 ms. For RT2, we also found a significant main effect of SOA, *F* (3,84) = 395.4, *p* < .001: RT2 increased on shorter SOAs. This difference is pronounced (effect size: 104 ms, 173 ms, and 150 ms respectively) and significant between all levels, *F*(1,28) = 179.6, *p* < .001; *F*(1,28) = 344.1, *p* < .001; F(1,28) = 105.6, *p* < .001 respectively. The typical, descending slope of RT2 over time showed the decreasing interference between the two tasks with decreasing task overlap. In short, a standard PRP effect was obtained.

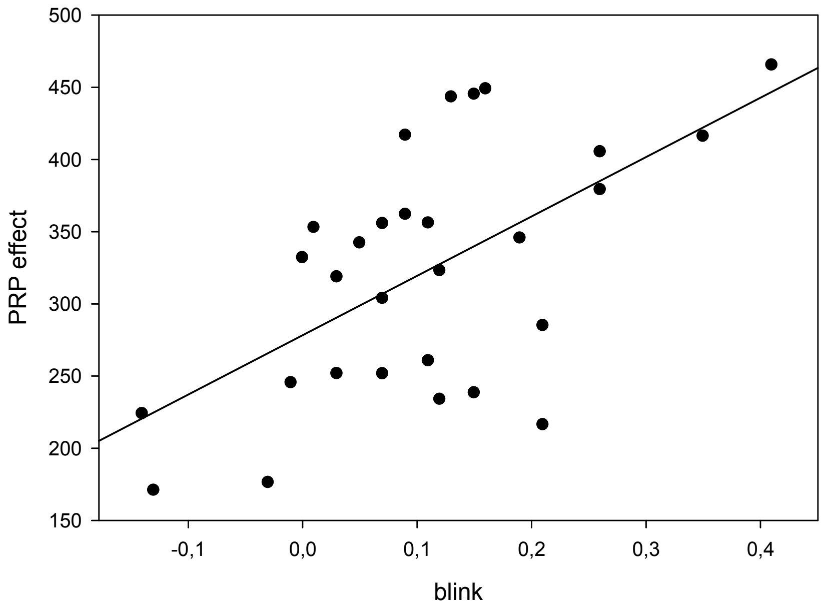

Figure 3.5. Correlation between PRP effect and AB.

Correlations

PRP effect and AB magnitude were significantly correlated, $r^2 = .644$, $p < .001$: Increased slowing of RT2 with more task-overlap in the PRP paradigm correlated positively with an increased difficulty to report T2 at short lags in the AB paradigm (see Figure 3.5). Partialling out the constructs IQ and WM operation span kept the correlation between the PRP effect and the AB significant, $r^2 = .558$, $p < .01$.

As expected, we found a significant correlation between WM operation span and IQ, $r^2 = .377$, $p = .044$[1]. This is consistent with earlier research showing that these two constructs overlap without being identical (Conway et al., 2003; Süβ et al., 2002).

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[1] This correlation is not as strong as is normally found between WM operation span and IQ, mainly due to the small IQ range used in this study. Because we used a student population only, IQ was limited to a range of 100-140.

There was a significant correlation between the AB magnitude (measured as T2|T1 at lag 8 minus T2|T1 at lag 3) and WM operation span, $r^2 = -.520$, $p = .004$[1], but not between AB magnitude and IQ, $r^2 = -.215$, $p = .263$ (see Figure 3.6). Partialling out the effect of IQ did not remove the correlation of AB magnitude and WM operation span, $r^2 = -.485$, $p = .009$. When we partialled out WM operation span, the correlation between AB magnitude and IQ remained non-significant, $r^2 = -.024$, $p = .903$. These results confirm the contribution of WM operation span in AB performance as found by Colzato et al. (2007): participants with a higher WM operation span showed a smaller AB magnitude, i.e. their performance on lag 3 for T2 is less impaired than the performance of participants with a low WM operation span.

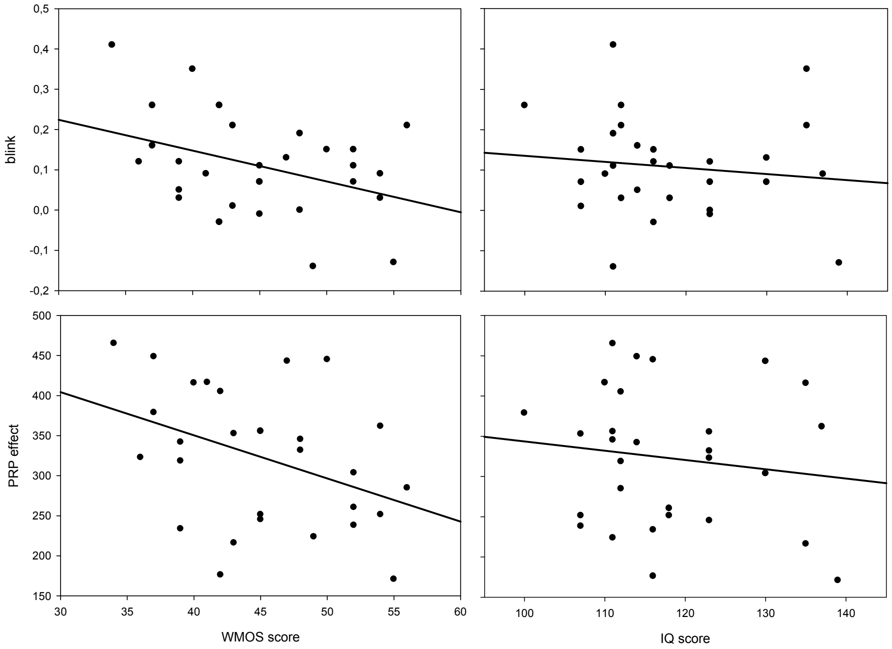

Figure 3.6. Correlation between PRP effect and WM operation span and IQ, and the correlation between the AB and WM operation span and IQ

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[1] For this experiment, AB effect size was calculated by subtracting conditional T2 performance at lag 8 from conditional T2 performance at lag 3; but taking the AB size as the difference between performance at lag 8 and the minimal performance at lags 3 and 5 gives similar results (for a further discussion see Colzato et al., 2007).

The PRP effect (measured as the absolute difference between RT2 at SOA = 900 ms and RT2 at SOA = 100 ms)[1] also correlated significantly with WM operation span, $r^2 = -.398$, $p = .033$ (see Figure 3.6). This result shows that participants with a higher WM operation span show a smaller PRP effect. The PRP effect did not correlate with IQ, $r^2 = -.199$, $p = .301$. Partialling out the effect of IQ reduced the correlation between PRP effect and WM operation span to a tendency, $r^2 = -.356$, $p = .063$, but note that the IQ-related reduction in explained variance was comparable to the reduction observed for the correlation between AB and WM. After partialling out the contribution of WM operation span, the correlation between PRP effect and IQ remained non-significant, $r^2 = -.058$, $p = .77$.

Apparently, the process-pure, IQ-controlled impact of WM operation span is more important and reliable in predicting the AB magnitude than in predicting the PRP effect. This might be taken to suggest that the part of WM operation span that predicts the PRP effect shares variance with IQ, whereas the part of WM operation span that predicts the AB magnitude does not. However, IQ affected the correlation between AB and WM on the one hand and that between PRP and WM on the other in similar ways, resulting in mild, comparable reductions of explained variance. Moreover, it may be that the AB task was more difficult or demanding than the PRP, so that WM resources were taxed less in the PRP task—which may explain why WM measures predicted AB performance better than they predicted PRP performance.

Regression

We conducted a hierarchical regression analysis with individual AB magnitude as dependent variable and individual IQ score as predictor and found no significant contribution for IQ ($ß = -.215$, $t = -1.144$, $p = .263$, $R^2 = .046$). Adding individual WM operation span scores ($ß = -.512$, $t = -2.830$, $p = .009$, $R^2 = .271$) improved the prediction, $F(2,26) = 4.8$, $p = .016$, $\Delta R^2 = .225$, showing the importance of WM operation span in modulating the AB magnitude.

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[1] This effect is a measure of the delay on RT2 that is caused by prior S1 presentation (e.g., at SOA = 900 ms, the response to S1 has already been given and the interference of S1 on RT2 is minimal). At SOA = 0 ms this interference is maximal. By calculating the so-called PRP effect as the difference in RT2 when SOA is 900 ms and the RT2 when SOA is 100 ms we obtained a measure of the interference that was caused by S1 on RT2. Using an SOA of 0 ms instead of an SOA of 100 ms would give similar results but, because of additional problems of presenting two stimuli simultaneously (mostly attentional problems), using the 100 ms SOA provides the purest estimate.

Next, we conducted a hierarchical regression analysis with individual PRP effect as dependent variable and individual IQ score as predictor and found no significant contribution of IQ (*ß* = .199, *t* = 1.056, *p* = .301, R^2 = .040). Adding individual WM operation span scores tended to improve the prediction (*ß* = .376, *t* =1.940, *p* = .063, R^2 = .161), which however did not account for a substantial amount of the variance, *F* (2,26) = 2.5, *p* = .102, ΔR^2 = .121.

Taken together, the regression analyses show, similar to the correlations, that WM operation span is a reliable predictor of AB magnitude but a weaker predictor of the PRP effect.

Discussion

The main purpose of the present study was to see whether, and to what degree individual differences in the performance on two types of dual tasks—the AB and the PRP task—would covary. If they would, so the idea, this would suggest that the mechanisms or capacity limitations underlying them are related, as suggested by Jolicœur and Dell'Acqua (1999) and others. Consistent with our first hypothesis, we indeed observed a strong correlation between the individual sizes of the AB - and PRP effect: Participants who were less capable of detecting flashing targets that rapidly followed others also showed a longer delay of responding to the second stimulus that rapidly followed another.

Our second hypothesis was related to the way the AB magnitude and the PRP effect are modulated by individual differences in WM capacity. The individual magnitude of the AB has been shown to depend on operation span, a measure of mainly the executive-control component of WM (Arnell et al., in press; Colzato et al., 2007). We found the same relationship but, more importantly, were able to obtain a similar relationship between the individual magnitude of the PRP effect and operation span. That is, both AB magnitude and PRP effect seem to be related to the executive-control component of WM, another sign that these two effects are functionally related.

Our third hypothesis was related to the impact of IQ on AB magnitude and PRP effect, and on the relationship between these effects and WM capacity. On the one hand, IQ as measured by the Raven's SPM (Raven et al., 1988) affected the two measures and their relationship with WM in very similar ways. Neither PRP-effect nor AB–magnitude effect sizes were directly predicted by IQ, and partialling out IQ reduced AB magnitude - OSPAN and PRP effect - OSPAN only mildly and to the same degree. On the other hand, however, controlling for IQ did render the correlation between PRP effect and OSPAN as a measure for WM operation span unreliable while leaving the correlation between AB magnitude and OSPAN significant. Clearly, this was due to that the latter correlation was stronger than the former in the first place, so that the IQ-induced reduction of the explained variance “hit” the weaker correlation harder.

This raises the question why OSPAN correlated more strongly with AB magnitude than with PRP effect. One possibility is that both effects reflect WM capacity limitations but these limitations have more severe consequences for the AB task than they have for the PRP task. A major role of WM in the AB task might consist in the suppression of the distractors or of preventing them from access to memory buffers. Vogel, McCollough, & Machizawa (2005) used a visual memory task in which they presented targets and distractors while obtaining electrophysiological measures of how much WM capacity was allocated. Results showed that people with a high WM operation span size were better able to prevent distractors from entering into WM. In the AB paradigm with the RSVP of many distractors, the blocking out of those distractors will be more important than in the PRP paradigm, where distractors do not play a role and where selecting appropriate responses and keeping the two tasks separate may pose the bigger problem. In other words, AB tasks may be more taxing with respect to WM capacity than PRP tasks in general, or at least with the particular task versions we used in the present study.

Taken altogether, our findings provide strong support of a common functional basis underlying the AB magnitude and the PRP effect, as suggested by Jolicœur (1999) and Jolicœur and Dell’Acqua (1999). This does not exclude the possibility that there are components that are not shared by the two tasks, as some authors have considered (Arnell et al., 2004; Arnell & Duncan, 2002; Wong, 2002). Indeed, even though the correlations between AB- and PRP effects, and between these effects and WM operation span, were reliable, they were far from explaining all of the variance, and there was even evidence for different degrees of sharing with WM-related variance. Further research is thus needed to identify such possible sources of non-shared variance, and the present study suggests that considering individual differences provides a valuable tool in this endeavor.

Chapter 4

How does Mental Rotation affect T2 Spatial Attention in a Psychological Refractory Period Paradigm: Behavioural and Neurophysiological Measures

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Bernhard Hommel, & Pierre Jolicœur

Manuscript in preparation

Abstract

Dual tasks and their associated delays have often been used to examine the boundaries of processing in the brain. We combined the dual-task method with the event-related potential (ERP) method to investigate how mental rotation of a first stimulus (S1) influences the shifting of visual-spatial attention to a second stimulus (S2). Visual-spatial attention was monitored by using the N2pc component of the ERP. In addition, we examined the sustained posterior contralateral negativity (SPCN) believed to index the retention of information in visual short-term memory. We found modulations of both the N2pc and the SPCN, suggesting that engaging mechanisms of mental rotation impairs the deployment of visual-spatial attention and delays the passage of a representation of S2 into visual short-term memory. Both results suggest interactions between mental rotation and visual-spatial attention in capacity-limited processing mechanisms indicating that response selection is not pivotal in dual-task delays and all three processes are likely to share a common resource like executive control.

Introduction

Performing two tasks at the same time can overload the capacity of the brain in such a way that performance is delayed or impaired. And yet, some combinations of tasks seem to be easier to perform than others, suggesting that the costs of multitasking depend on the types of cognitive processes that overlap in time. A particularly helpful tool in telling apart processes that do and do not produce dual-task costs is the so-called Psychological Refractory Period (PRP) paradigm (Telford, 1931). This paradigm commonly involves a dual task (Task 1 and Task 2, or T1 and T2) in which two stimuli (S1, S2) are presented that each require a speeded response (R1, R2). The two stimuli are separated in time by a Stimulus Onset Asynchrony (SOA), so to manipulate the temporal overlap of the two tasks. Results typically show an increased reaction time (RT) to S2 (RT2) with decreasing SOA, suggesting that some process necessary to carry out the second response needs to wait until some other process in the first task has been completed—this is called the PRP effect (Welford, 1967).

Under the assumption of a single capacity limitation, the combined effect on RT2 of SOA and a T2 variable can clarify which processes are deferred in the PRP paradigm. If the effect of a T2 variable onto RT2 is equal for short and long SOAs (i.e., additive with the SOA effect), this implies that the T2 effect is related to a capacity-limited T2 process or some other process following this capacity-limited process. If instead the effect of the T2 variable is smaller for short than for long SOAs (i.e., combines underadditively with the SOA effect), this implies that the T2 effect arises before capacity-limited processes. Underadditive effects are thought to occur because at short SOAs capacity-limited processes are deferred, and this causes a state of slack for T2 processes. This slack in a sense “swallows” at least part of the T2 effect, so that a T2 variable that affects processes preceding the capacity limitation in T2 delays RT2 for a shorter while with short than with long SOAs (Pashler & Johnston, 1989). Assume, for instance, decreasing the visibility of S2 would delay RT2, but this effect would impact a process that precedes the true dual-task bottleneck. With a short SOA, T2 is likely to have to wait longer than the visibility effect would delay RT2, so that during that slack time any possible visibility problem can be resolved before T2 continues. With a long SOA, there is no waiting time and thus no slack, so that the visibility effect would fully contribute to RT2. Additional clues about which processes are capacity limited can come from the effect of T1 variables onto RT2. Effects of T1 variables on capacity-limited processes or earlier will defer T2 processes and affect RT2, whereas T1 variables that take effect after capacity-limited processes will not affect RT2.

A number of studies have applied this reasoning with considerable success to the PRP paradigm (e.g., Carrier & Pashler, 1995; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachman, 1995). Pashler and Johnston (1989) conducted a dual task with two choice RT tasks. T1 was a tone identification task and T2 involved a choice response to one of the letters A, B, and C. S2 perceptual difficulty and stimulus repetition were varied to affect the duration of perceptual processes and response selection, respectively. The effects of SOA on RT2 were underadditive with the effect of perceptual difficulty, and additive with that of stimulus repetition. These results are in line with a response-selection bottleneck model (Pashler, 1994; Smith, 1967; Welford, 1952; 1980), which assumes that response selection is the major bottleneck in multitasking, in the sense that only one response can be selected at a time.

Even though the response-selection bottleneck model has been very successful in explaining a wide variety of observations (see Pashler, 1994, for an overview), there is increasing evidence that response selection is not the only cognitive process with bottleneck characteristics. In the present study, we focused on two processes that based on previous observations can be suspected to have such characteristics: mental rotation and the shifting of visual-spatial attention. In contrast to previous studies that investigated the interaction between these processes and response selection, we were interested in the direct interaction between mental rotation and attentional shifting. Before we describe the rationale of our study in more detail, we first review the available evidence suggesting that mental rotation and attentional shifting might indeed possess bottleneck characteristics.

Mental rotation

In a mental-rotation task, participants categorize asymmetric visual stimuli, such as (most) letters, as normally oriented versus mirror-reversed. Importantly, the stimuli are rotated to some angle from their usual upright orientation, which makes the task more difficult. Results show that RT increases more or less linearly with increasing angle from normal orientation (Cooper, 1975, 1976; Cooper & Shepard, 1973; Shepard & Metzler, 1971). Although the mechanisms underlying this observation are still largely unknown, the empirical findings are very robust and replicable (see Shepard & Cooper, 1982, for a review). As suggested by the study of Corballis (1986), the mirror/normal discrimination can only be made if participants have actually carried out something like a mental rotation of the stimulus representation into its normal upright position. This process is assumed to have analog characteristics, so that stimuli that deviate more strongly from their normal position have to be “mentally rotated” for a longer time—which is taken to explain the linear relationship between RT and rotation angle.

From a response-selection bottleneck model, one would not expect that mental rotation as indexed in such a comparison task shares resources with response selection. And yet, there is evidence suggesting this possibility. A number of studies have looked into the interactions between mental rotation and response selection in a PRP paradigm. With a mental-rotation task as T2, Ruthruff et al. (1995) observed that a large proportion of the T2 orientation effect was still present at very short SOAs and concluded that mental rotation shares limited capacity with response selection in T1. Comparable findings were reported by Van Selst and Jolicœur (1994), Heil, Wahl, and Herbst (1999), and others, and Band and Miller (1997) observed that mental rotation interferes with concurrent response preparation. Taken together, these studies provide strong evidence that mental rotation has bottleneck properties similar to response selection.

Visual-spatial attention shifting

Considering their different computational functions the observed similarities between mental rotation and response selection may seem rather surprising. Probably less surprising are commonalities between visual attention shifting and response selection. The main function of a response-selection process should be the identification and activation of the cognitive representation of an action that meets the current situational requirements and task goals. Visual attention often serves comparable purposes by identifying and activating the cognitive representation of a relevant stimulus or target, and by optimizing the collection of information about this stimulus by directing attention to its location in space. Accordingly, if response selection draws on cognitive resources to a degree that renders it an effective processing bottleneck, it makes sense to assume that stimulus selection does the same. Investigations of the possible bottleneck characteristics of visual attention shifting turned out to be rather varied however.

A first study addressing this issue was reported by Pashler (1991), who investigated the potential bottleneck properties of visual-spatial attention in a dual task. In his PRP study, T1 was a tone identification task and T2 was an unspeeded masked-letter identification task. If spatial attention would have bottleneck properties, so the idea, accuracy on T2 would be impaired at short SOAs, that is, if response selection in T1 would temporally overlap with directing attention in T2. In view of an actually significant but small interaction of T2 performance and SOA, Pashler concluded that visual-spatial attention does not have bottleneck properties.

Along the same lines, Johnston, McCann, and Remington (1995) asked whether attention is one unitary process comprising of both input selection and output selection or rather a set of separate and dissociable selection processes. They conducted a spatial-cuing experiment and a PRP experiment, which both included a letter-identification task with undistorted and distorted stimuli. In the spatial-cuing experiment, only the letter-identification task was used and the location of the letter was pre-cued validly in 80% of the trials. In the PRP paradigm, the letter-identification task served as T2 that was combined with a tone-discrimination task as T1. The rationale was that the cuing effect would tap into input selection, whereas the PRP effect (because of its known relation to response selection) would tap into output selection. If input and output selection would draw on common resources, so the authors argued, effects related to both types of selection should interact with the same variables, such as that of letter distortion. However, the spatial-cuing task showed additive effects of letter distortion and cue validity, whereas the PRP task showed underadditive effects of letter distortion and SOA. Accordingly, Johnston et al. (1995) argued that input and output attention can be seen as a set of related but separate selection processes, in which response selection—conceived of as “central”, capacity-limited process—prevents the simultaneous execution of other capacity-limited processes, whereas the deployment of visual-spatial attention can overlap other capacity-limited or unlimited processes. But note that this conclusion was drawn from a comparison across two separate experiments, without directly looking into the interaction between response selection and attentional shifting.

Even though these first studies did not seem to provide strong evidence for the idea that shifting visual attention might possess bottleneck properties, more recent studies that used event-related brain potentials (ERP) have changed the picture considerably. Brisson and Jolicœur (2007a, 2007b) showed how the N2pc component (a negative posterior contralateral component that peaks usually after 200-300 ms) can be used to monitor visual-spatial attentional processes on a moment-to-moment basis (Brisson & Jolicœur, 2007a; 2007b; Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 2003). The N2pc is calculated by subtracting ERPs over ipsilateral from ERPs over contralateral electrode positions, relative to the visual hemifield of the target. The difference waves for targets in the left and right hemifield are then averaged. The N2pc is generally observed on the lateral posterior sides of the head, usually with a maximum amplitude at electrode-pair PO7 / PO8. Other nearby electrode-pairs are sometimes also measured and included in pooled waveforms, together with the waveforms observed at PO7 / PO8 (e.g., Brisson & Jolicœur, 2007a; Eimer, 1996; Woodman & Luck, 2003). The neural generators of the N2pc are likely in extrastriate visual cortex (Hopf et al., 2000; Hopf & Mangun, 2000).

Brisson and Jolicœur (2007a) used a PRP paradigm in which they presented a tone discrimination task for the first task that was either easy (the highest or the lowest tone) or difficult (the middle two tones) to distinguish. In the second task, subjects had to shift covert attention to a specified colored square presented in the left or right visual field and the N2pc was measured. S2 was presented at different SOAs (300, 650 or 1000 ms), or in different conditions of central load, in different variants of the PRP paradigm. The general finding was that the amplitude of the N2pc was reduced when central load at the time of presentation of S2 was increased (e.g., by decreasing SOA). Such results suggest that the deployment of visual-spatial attention is impaired by PRP interference, which in turn suggests that shifting visual-spatial attention does require capacity-limited processing mechanisms that overlap with those that lead to the PRP effect—such as response selection.

Following the N2pc, the contralateral minus ipsilateral waveform often has a sustained posterior contralateral negativity (SPCN). A growing body of work provides strong arguments for a functional interpretation of the SPCN as a reflection of stimulus encoding in visual short-term memory (VSTM; Jolicœur, Brisson, & Robitaille, 2008; McCollough, Machaziwa, & Vogel, 2006; Perron et al., 2008; Predovan et al., 2008; Robitaille & Jolicœur, 2006; Vogel & Machizawa, 2004). Like the N2pc, the SPCN is a greater negativity at posterior electrodes contralateral to the side from which visual information was encoded. The onset latency of the SPCN is around 300 ms and the component often has a lengthy sustained period. Interestingly, the amplitude of the SPCN increases as the amount of information held in VSTM increases (Jolicœur et al., 2008; McCollough et al., 2006; Perron et al., 2008; Vogel & Machizawa, 2004) with a plateau reached when the number of stored items equals the capacity of VSTM (Vogel & Machizawa, 2004). In Brisson and Jolicœur's (2007a) PRP experiment with an easy versus difficult response selection for T1 and a covert visual-spatial attention shifting task for T2, SPCN onset was delayed when T1 response selection was more difficult. Brisson and Jolicœur (2007a) argued that the encoding of information into VSTM was delayed and that T2 early sensory specific visual-spatial attention was postponed by T1 response selection. These results are in line with the results obtained for the N2pc.

To summarize, electrophysiological evidence suggests that shifting visual-spatial attention has bottleneck properties, in the sense that performance is impaired if attention needs to be shifted concurrently with other capacity-demanding processes. Process overlap has at least two separable consequences: the delay of the N2pc, which is associated with, and presumably represents the attentional shift itself, and the delay of SPCN, which is associated with, and presumably represents the encoding of selected items into VSTM. In other words, temporal overlap impairs both the shifting process proper and the consequences of shifting for succeeding memory processes.

The present experiment

The increasing evidence that processes other than response selection processes contain bottleneck characteristics challenges the traditional response-selection bottleneck model. Apparently, it is not just rather “late” operations that draw heavily on sparse cognitive resources, but also operations that select stimulus information and/or reprocess and prepare it for further processing. However, previous studies providing such evidence have always tried to validate their conclusions by demonstrating interactions with response selection or at least with PRP effects related to response selection. Accordingly, the available findings are still consistent with the possibility that response selection plays a pivotal role—so that one may argue that the response-selection bottleneck model could simply be extended by assuming that some capacity can be shared between response selection proper and other (still to be defined) processes. To rule out this possibility we aimed at demonstrating that PRP-type interference can be observed between processes that do not involve response selection at all.

Given the strong evidence that both mental rotation and the shifting of visual-spatial attention interact with response selection, we sought to pit these two processes against each other directly. We thereby took advantage from the fact that mental rotation is a rather well-defined process and that its duration can be systematically manipulated by varying the orientation of the target stimulus to normal upright. In particular, we carried out a PRP experiment, in which T1 was a mental-rotation task and T2 required a covert shift of the focus of visual-spatial attention. In the mental-rotation task stimuli were presented either in their upright position or rotated from this position by 140°. The latter condition can be estimated to keep the mental-rotation operation active for approximately 250 ms, so that dual-task interference from mental rotation on attention can be reliably measured. The SOA variation across the levels of 300 and 650 ms provided a different way to diagnose dual-task interference, because this manipulation affects the timing of response selection independent of mental rotation. In T2, participants responded to a colored square in a set of four visual stimuli, two on either side of the screen center. Just as in recent studies by Brisson and Jolicœur (2007a, 2007b), the N2pc and SPCN were measured as indicators of the deployment of visual-spatial attention to, and VSTM storage of stimuli in T2.

According to the traditional response-selection bottleneck model the deployment of attention does not have bottleneck properties (Pashler, 1991), suggesting that neither N2pc nor SPCN would be affected by either SOA or the concurrent mental rotation required in the rotation condition. If instead the deployment of attention is subject to the same capacity limitations as response selection, as argued by Brisson and Jolicœur (2007a, 2007b), an SOA effect is predicted on the N2pc amplitude and the SPCN onset latency. Moreover, if response selection, mental rotation, and the deployment of attention are all subject to the same capacity limitations, then the N2pc and SPCN should be affected by both S1 orientation and SOA.

Methods

Participants

Thirty right-handed students of Leiden University aged between 18 and 30 participated in this experiment. The experiment was conducted in accordance with relevant laws and institutional guidelines and was approved by the local ethics committee from the Faculty of Social Sciences. All students had normal or corrected to normal eye-sight. They received either fourteen euros or course credits or a comparable combination of both. Data from 10 participants did not comply with the electrophysiological criteria (described below) and were therefore discarded from analysis. Data from another four participants were excluded from analysis because behavioural performance was below a 74% threshold. This left 16 participants (four male) in the sample (mean age: 22.05 years).

Apparatus

Participants were tested individually, in a dimly-lit shielded room. Participants sat in front of a 17 inch computer screen at a viewing distance of approximately 75 cm. Responses were made with key-presses with the left and right foot for T1 responses and the left and right index finger for T2 responses. The pedals (Psychological Software Tools, Inc.) were embedded in a sloping footboard that was put in front of the participants in such a way that in rest, the participants' feet were relaxed. The pedals needed light pressing to give a response and an adequate response was marked by the click-sound of the pedal. Of the two response boxes for the fingers (one for each hand) with four keys (no key for the thumb) only the keys for the index fingers were used (situated closest to the middle).

Stimuli

The stimuli used in T1 were presented on the screen and were the alphanumeric characters 2, 4, 5, 7, f, G, k, Q, R and t. These stimuli were selected because their asymmetry allowed the creation of unambiguous rotation and mirroring conditions (hence the mixture of uppercase and lowercase letters). They were oriented either normally or left-right mirror-imaged and their orientation was 0 or 140°. Clockwise (CW) and counter-clockwise (CCW) tilted stimuli occurred equally often in case of the 140° condition. The characters were presented at the centre of the screen, in black on a grey screen, at a visual angle of approximately 3° in height. Because S1 was always presented in the middle of the screen, spatial capture was similar for both the conditions. Participants had to make a mirror/normal classification of the rotated stimulus.

For T2, four squares were presented in the bottom half of the screen, two on each side of the centre. The squares had two gaps, always on opposite sides. This way, an imaginary line could be drawn through the gaps, either vertically or horizontally. All squares in the visual display subtended a visual angle of 1° × 1° and the gaps were 0.33°. The centre of the squares nearest to fixation was 1.5° below and 3.5° to the left or right of fixation. The centre of the far squares was 3° below and 5° to the left or right of fixation (see also: Brisson & Jolicœur, 2007a). To prevent a pop-out effect of the target square on one side, there was always a blue colored square on each side of the centre, while of the two remaining squares one was green and one red (one on each side). The colors were isoluminant. Any bilateral electrophysiological activation due to low-level factors, other than attention, would cancel out when the N2pc and SPCN difference waves were calculated. The task was to indicate the orientation of the imaginary line (vertical versus horizontal) that could be drawn through the gaps of the green or the red square, and the color of the target square was constant for a given participant and counterbalanced across participants.

The two presented stimuli were separated by a SOA of 300 ms or 650 ms. SOA, mirror/normal presentation, rotation direction (CW/CCW), target orientation (0° or 140°), position of the squares and horizontal/vertical orientation of the gaps in the squares were all varied randomly within each block (See Figure 4.1 for an example of a trial).

Left foot and right foot presses were used for T1 responses and their meaning — either normally presented or in mirror image — was counterbalanced across participants. Left and right index finger presses were used for T2 responses and their meaning — horizontal or vertical line through the gaps in the target square — was also counterbalanced across participants, as was the color of the target square (red or green).

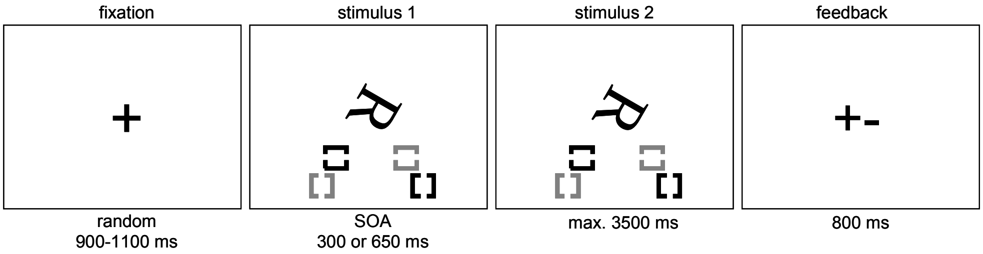


Figure 4.1. Sequence of events within one trial in the PRP paradigm: the '+' serves as a fixation, the S1 appears in the centre of the screen, and after a SOA of 300 ms or 650 ms, T2 and distractors appears on both sides below the centre of the screen. Feedback is presented at the end of each trial. The actual colors of the squares were blue (one on each side), red and green. The size of the letters, squares and their distances is not to scale.

Procedure

Before the start of the experiment, participants received written instructions. They were asked to respond as quickly as possible, and not to be too cautious in their response. To avoid response grouping, participants were told not to withhold the response to S1 until S2 was presented, but rather to initiate a response as soon as possible. Lastly, they were told to keep their eyes fixated in the centre of the screen (and not to make an eye movement to the sides) and to limit eye blinks to the time between the trials.

Next, the computer experiment was started. First, eye movements were measured using a calibration test in which participants needed to follow a target that moved from the centre to the left or the right side of the screen to measure horizontal eye movements. Second, the first task was practiced by itself, as a single-task (16 trials). Two dual-task blocks followed to practice the eventual task (32 trials per block).

Experimental trials were presented in 12 blocks of 74 trials. Pauses separated the blocks and participants were encouraged to use them. Within the experimental blocks, the trial started with the presentation of a fixation point in the centre of the screen replaced after 500 ms by S1. After a variable SOA S2 appeared while S1 remained in view. As soon as S2 appeared, participants had 3000 ms to respond before feedback appeared. Alternatively, responding to S2 also caused feedback to appear. Feedback consisted of a '+' or '-' sign left of the middle for S1 and right of the middle for S2 shown for 800 ms marking the end of the trial. After a jittered intertrial interval of 900–1100 ms the fixation point appeared in the centre of the screen to indicate the beginning of the next trial. At the end of each block, an average reaction time (RT) and a percentage correct (PC) for each task up to then was presented to give participants insight in their progress, and to motivate them to keep trying to respond faster on every block.

Electrophysiological measurements

Electrophysiological measures for the N2pc and the SPCN were recorded with 29 Ag/AgCl electrodes: Fz, F3, F4, FC3, FC4, C5, C3, C1, Cz, C2, C4, C6, T7, T8, CP3, CP4, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2 in the extended international 10/20 system (Sharbrough et al., 1991). The signal was digitized at 256 Hz. Eye movements and blinks were recorded by electro-oculogram (EOG). Horizontal EOG (HEOG) was the bipolar signal of the left versus right outer canthus and vertical EOG (VEOG) was the bipolar signal of above versus below the left eye. The signals for both the N2pc and the SPCN were high-pass filtered at 0.01 Hz (24 dB / octave) and low-pass filtered at 40 Hz (24 dB / octave).

Electrodes of interest were P7 / P8, PO7 / PO8, P3 / P4, PO3 / PO4, and O1 / O2 for the N2pc and SPCN. Artifacts at any of these electrode sites led to the exclusion of that particular trial as did eye blinks (VEOG > 100 µV). For the N2pc it was important to keep the eyes fixated at the centre of the screen: any trials containing large eye movement (HEOG > 35 µV) were therefore excluded. Comparable to Woodman and Luck (2003) and Brisson and Jolicœur (2007a), after ocular artifact rejection a 3.2 µV cut off was used for residual eye movements towards the targets (squares) in the average HEOG waveforms computed for trials with a target in the left visual field and for trials with a target in the right visual field. The ten participants exceeding this boundary in any of the conditions were excluded from further analysis.

For N2pc, segments of 200 ms prior to S2 presentation to 600 ms after S2 presentation were used, baseline corrected on the period from 200-0 ms before S2 presentation. We quantified the N2pc as the mean amplitude of the pooled difference (mean contralateral minus mean ipsilateral) waveform for the five posterior lateralized electrode pairs in our montage, in the time window of 190–260 ms from S2 onset. This time window best captures the outer limits of the negative N2pc-peak of all electrode-pairs across the four conditions.

The SPCN waves in the four main experimental conditions (SOA X S1 orientation) seemed to not yet have reached a plateau 600 ms after S2 onset. Especially at the short SOA - 140° S1 orientation condition, the SPCN wave was delayed. In order to determine whether the SPCN actually did reach a plateau, but only later, we extended the analysis window from 600 ms to 900 ms, and again, baseline corrected it on the period from 200-0 ms before S2 presentation. Using this longer analysis window, however, required that we removed the data of four participants, because the longer measurement window included many more trials with ocular artifacts and their elimination left too few trials for their data to be reliable. Thus, further analyses were based on a subsample of twelve participants.

The SPCN amplitude was analyzed to test for interference of S1 orientation and SOA with the normal continuation of processes underlying SPCN. The mean amplitude was calculated in the pooled response over posterior lateralized electrodes of the contralateral minus ipsilateral difference waveform where the SPCN was maximal: 380–500 ms relative to the onset of S2.

Onset latency was analyzed to test for deferment of the processes underlying SPCN by S1 orientation and SOA. This was done using the jackknife analysis (Kiesel, Miller, Jolicœur, & Brisson, 2008; Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). With the jackknife method, *N* grand average waveforms are computed, each one with *N*-1 participants (a different participant is removed for each waveform). Onset-latency measures are obtained for each of these *N* grand average waveforms, and the values are submitted to a conventional analysis of variance (ANOVA). In order to compensate for the smaller variance of the jackknife waveforms, the *F* value in the ANOVA is adjusted using the following formula (Brisson & Jolicœur, 2007a; 2007b; Ulrich & Miller, 2001): $F_{adjusted} = F / (N-1)^2$.

Before the SPCN onset was determined, waves were low-pass filtered at 3 Hz (24 dB / octave). The onset latency of the SPCN was defined as the latency at which the filtered pooled difference wave became more negative than -0.4µV, starting 300 ms after stimulus presentation.

Results

Behavioural results

RTs longer than 3000 ms or shorter than 150 ms and trials in which R2 preceded R1 were excluded from the analysis of RT and PC. The percentages of trials eliminated based on these restrictions were 0.94% for the S1 upright orientation/short SOA condition, 1.29% for the S1 rotated orientation/short SOA condition, 0.74% for the S1 upright orientation/long SOA condition and 1.06% for the S1 rotated orientation/long SOA condition. Mean RTs were based on trials with a correct response to both stimuli. We excluded all trials from the data in which R2 preceded R1, which happened in a total of 2.5% of the trials. ANOVAs were conducted using a 2 × 2 design with the within-subjects factors S1 orientation and SOA and an alpha of 0.05. We used the Greenhouse-Geisser Epsilon (Jennings & Wood, 1976) to correct the *p* and *MSE* where appropriate (but original *df*'s are reported). Table 4.1 shows the mean behavioural performance data.

Table 4.1. Mean reaction times and percentages correct for Task 1 and Task 2, in each condition, with SEM (standard error of the mean) in parenthesis

	RT1		PC1		RT2		PC2	
SOA (ms)	300	650	300	650	300	650	300	650
S1 upright	851	874	94	95	947	750	92	89
(0°)	(46)	(47)	(0.6)	(0.5)	(69)	(52)	(1.7)	(2.3)
S1 rotation	1101	1120	85	84	1179	887	92	90
(140°)	(54)	(45)	(1.4)	(1.8)	(76)	(63)	(1.6)	(2.0)

Mean S1 accuracy did not change over SOA, *F* < 1, and mean RT1 did not vary significantly over SOA, *F*(1, 15) = 2.6, *MSE* = 2179.2, *p* > .10. S1 orientation did affect the accuracy of responses to S1: the percentage correct was higher with an upright (easy condition) than a rotated S1 (difficult condition; 94.4% versus 85.7%), *F*(1, 15) = 60.4, *MSE* = 20.1, *p* < .001, and RT1 was also shorter in the upright condition (857 versus 1107 ms), *F*(1, 15) = 264.9, *MSE* = 3757.7, *p* < .001. There was no interaction effect between SOA and orientation for S1 accuracy or RT, *F*s < 1.

RT2 for the rotated and upright orientation are shown in Figure 4.2. For T2, there was no significant difference in percentage correct as a function of S1 orientation, *F* < 1. RT2 was shorter at 0° than at 140° (823 versus 1016 ms), *F*(1, 15) = 195.0, *MSE* = 3060.1, *p* < .001. We found a significant effect of SOA, *F*(1, 15) = 7.2, *MSE* = 5.0, *p* < .05, for T2 accuracy. Responses were 1.5% more accurate at a SOA of 300 as compared to 650 ms (92.8% versus 91.3%). Mean RT2 increased by 253 ms with decreasing SOA (from 793 ms to 1046 ms), *F*(1, 15) = 394.2, *MSE* = 2615.0, *p* < .001, showing the expected PRP effect. Additionally, the interaction effect of S1 orientation and SOA on RT2 indicated that the orientation effect was larger at short than at longer SOAs, *F*(1, 15) = 112.2, *MSE* = 393.4, *p* < .001. There was a marginally significant interaction effect for the percentage correct of T2, *F*(1, 15) = 3.1, *MSE* = 5.2, *p* < .10.

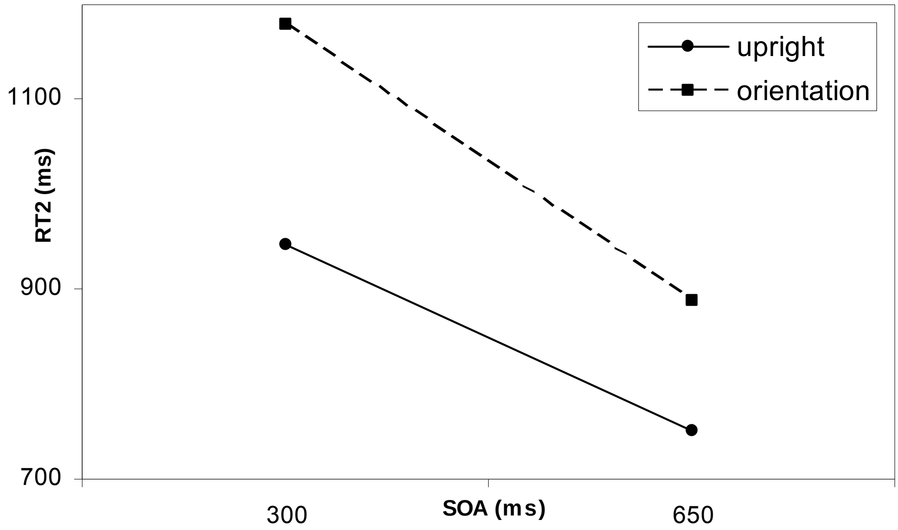


Figure 4.2. The interaction between Task 1 difficulty and SOA on RT2

Electrophysiological results

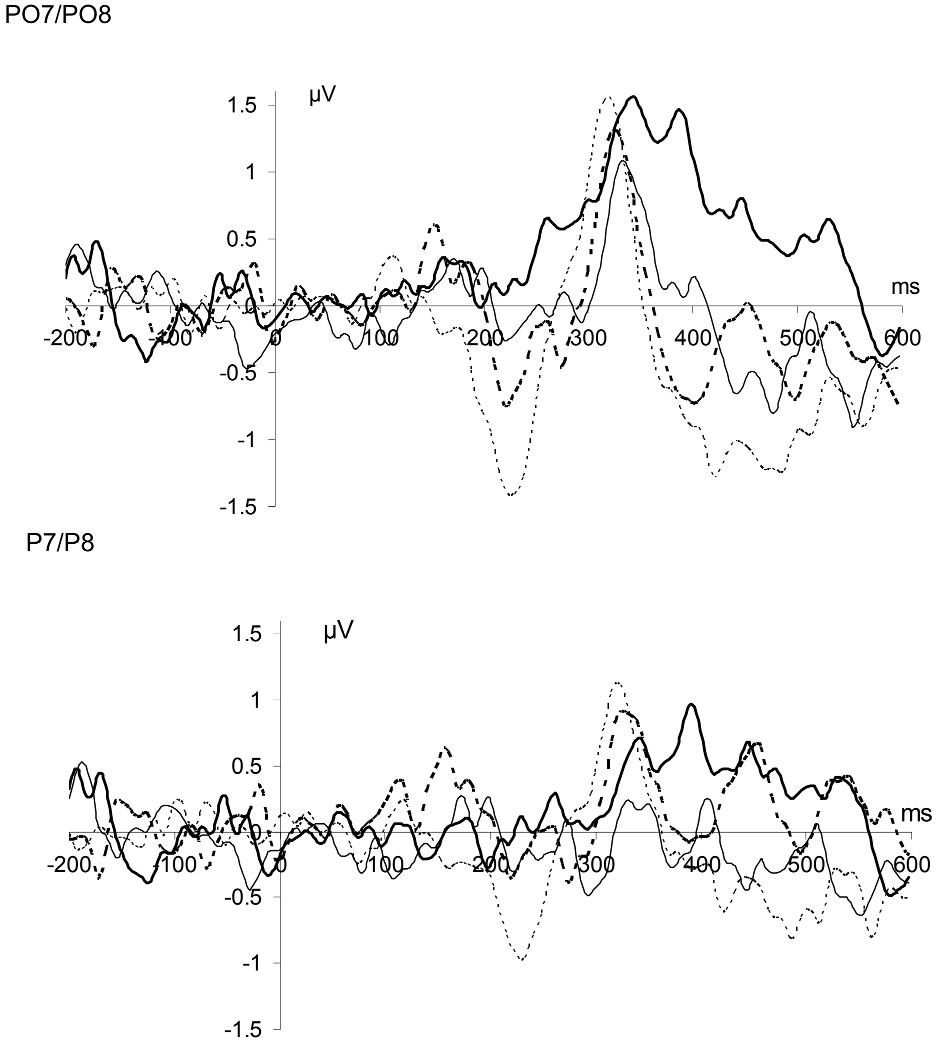
N2pc

The mean N2pc amplitudes were submitted to an ANOVA with S1 orientation, SOA and electrode position as within-subjects factors. The contralateral minus ipsilateral waveforms are shown in Figure 4.3. The effect for S1 orientation was significant, *F*(1, 15) = 5.4, *MSE* = 1.0, *p* < .05, due to less negative amplitude of the N2pc if S1 was rotated. There was also a significant main effect of SOA, *F*(1, 15) = 14.4, *MSE* = 1.3, *p* < .01, indicating that the amplitude of the N2pc was attenuated at short SOA relative to long SOA. No other effect was reliable.

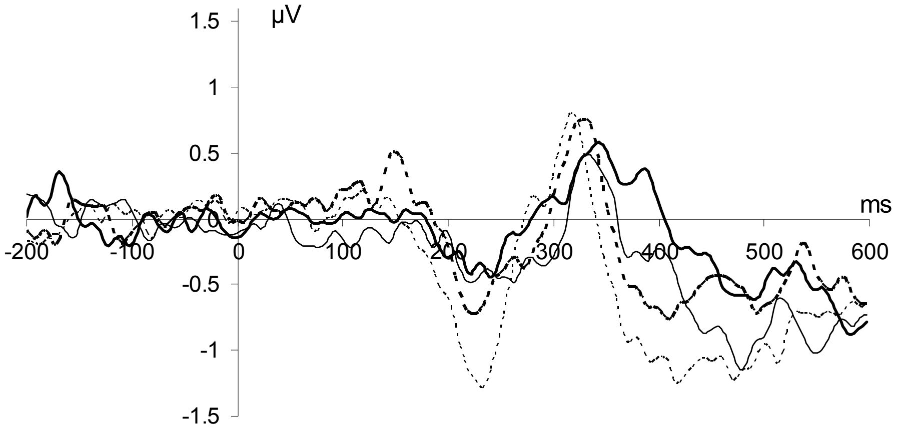
For an independent test of dual-task interference onto the N2pc due to response selection, we examined the effect of SOA for trials with an upright S1, if thus no mental rotation was required. There was a significant attenuation for the short relative to the long SOA, *F*(1, 15) = 12.9, *MSE* = 1.3, *p* < .01. This contrast confirms that response selection in itself delays visual-spatial attention in a following task, as observed by Brisson & Jolicœur (2007a, 2007b).

Similarly, for an independent test of dual-task interference onto the N2pc due to mental rotation, we examined the effect of S1 orientation for the long SOA level; when the PRP effect is typically at its minimum. At SOA = 650 ms, a S1 in 140° orientation produced an attenuated N2pc compared to a S1 in upright position, *F*(1, 15)

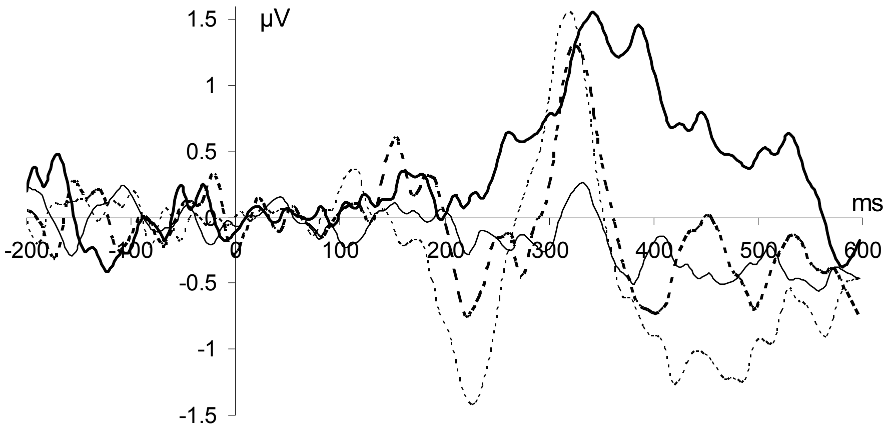
= 4.9, *MSE* = 1.6, *p* < .05. At SOA = 300 ms, the effect of orientation was not significant, *F* < 1, presumably because the N2pc of the upright position condition was already attenuated because of the short SOA. This result shows that indeed mental rotation interferes with visual-spatial attention, independent of response selection.



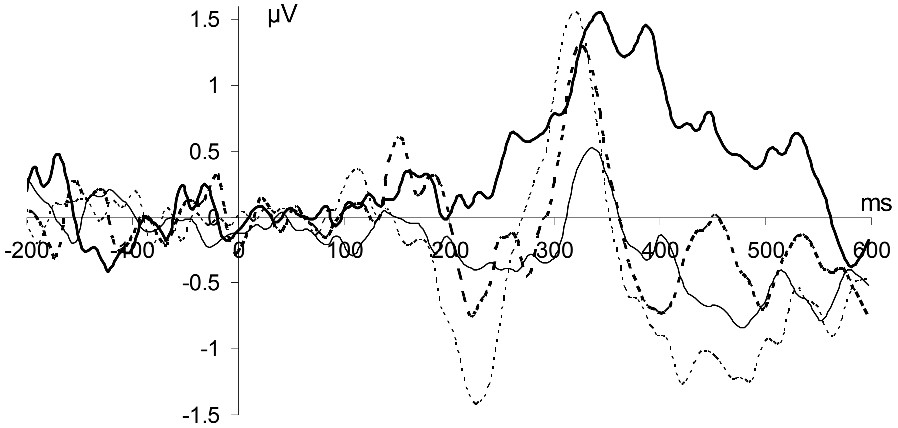
O1/O2



PO3/PO4



P3/P4



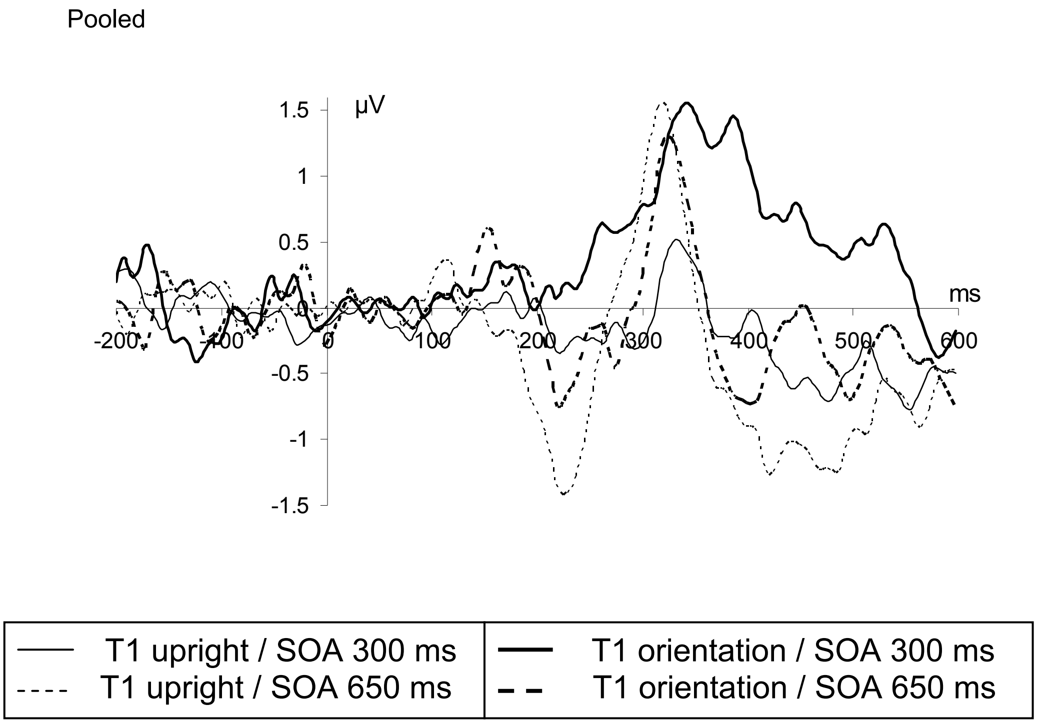
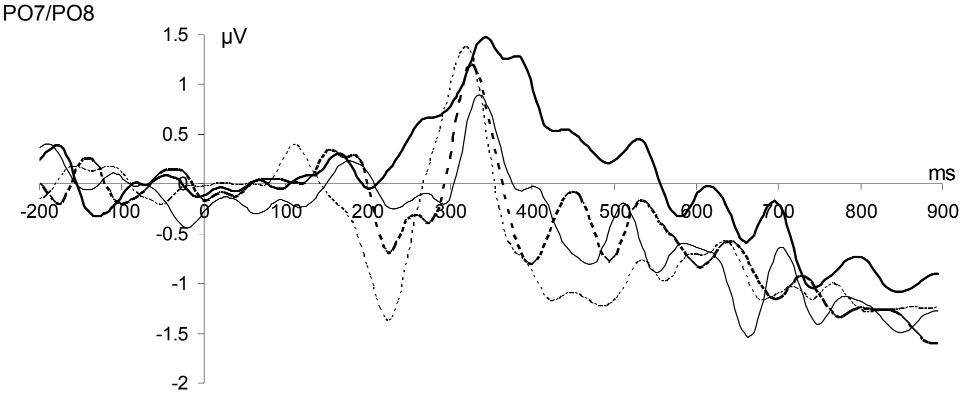


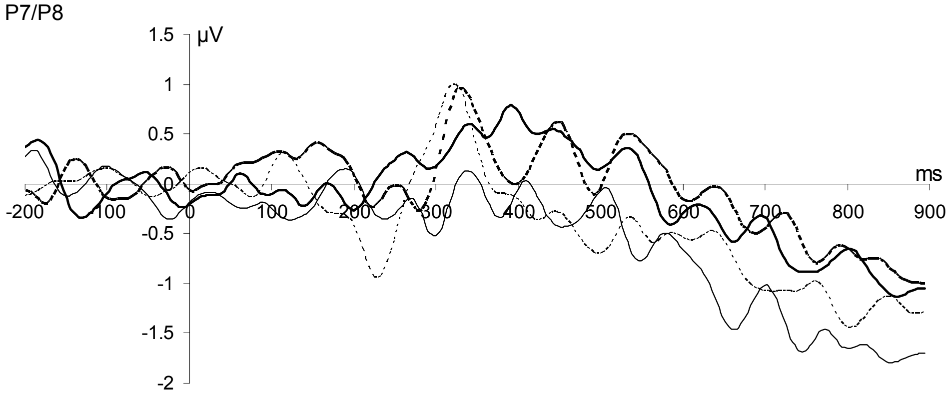
Figure 4.3. N2pc and SPCN stimulus locked to T2, for the four different conditions: S1 0º / 300 ms SOA; S1 0º / 650 ms SOA; S1 140º / 300 ms SOA; S1 140º / 650 ms SOA for the subtracted signals PO7 / PO8, P7 / P8, O1 / O2, PO3 / PO4, P3 / P4 and their pooled waveform. A 15 Hz filter was used on a waveform that started 200 ms before stimulus onset and ended 600 ms after stimulus onset. Thin lines represent S1 0º orientation, bold lines represent S1 140º orientation, straight lines represent short SOA and dotted lines represent long SOA.

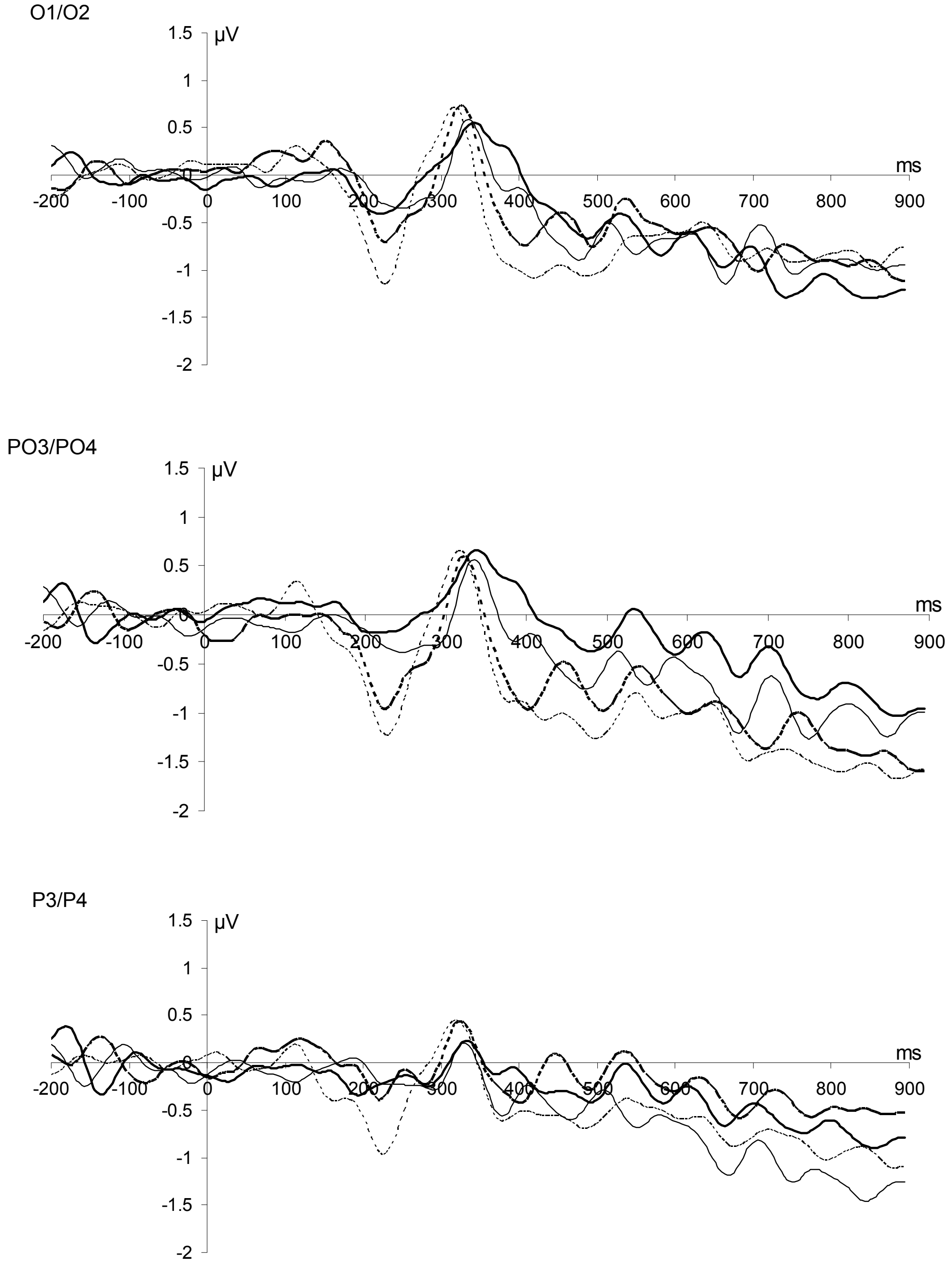
SPCN amplitude

The mean amplitude of SPCN in the sample that met our inclusion criteria for the longer window was submitted to an ANOVA with the factors orientation (2), SOA (2) and electrode (5). The lateralization waveforms are shown in Figure 4.4. The main effect of S1 orientation was significant, *F*(1, 11) = 6.6, *MSE* = 3.4, *p* < .05. The mean SPCN amplitude was less negative when S1 was at a 140° orientation than for upright S1. There was also an effect of SOA, *F*(1, 11) = 8.8, *MSE* = 1.7, *p* < .05: reflecting a smaller SPCN on short than on long SOAs. The main effect of electrode position was also significant with a maximum effect over electrode pairs O1 / O2 and P3 / P4 and decreasing activity with further distance from those electrode pairs, *F*(4, 44) = 4.8, *MSE* = 1.6, *p* < .01. S1 orientation and SOA did not interact, *F* < 1, nor did S1 orientation and electrode position, *F*(4, 44) = 1.3, *MSE* = 0.740, *p* > .10. The interaction of SOA and electrode position did reach significance, *F(*4, 44) =3.7, *MSE* = 0.645, *p* < .05. The effect of SOA was maximal over electrode pairs O1 / O2 and P3 / P4 with decreasing activity with further distance from those electrode pairs, and overall more activity at the long SOA than at the short SOA.

As a test for comparability, the SPCN amplitude in the *full sample* of participants was also analyzed again in the 350-500 ms time window in the smaller measurement window and showed the same results. Similarly, the N2pc amplitude in the *reduced sample* was analyzed again in the 190–260 ms time window. This led to the same pattern of effects as in the full sample.






O1/O2
1.5
µV
1
0.5
ms
-200
-100
0
100
200
300
400
500
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900
-0.5
-1
-1.5
-2
PO3/PO4
1.5
µV
1
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-200
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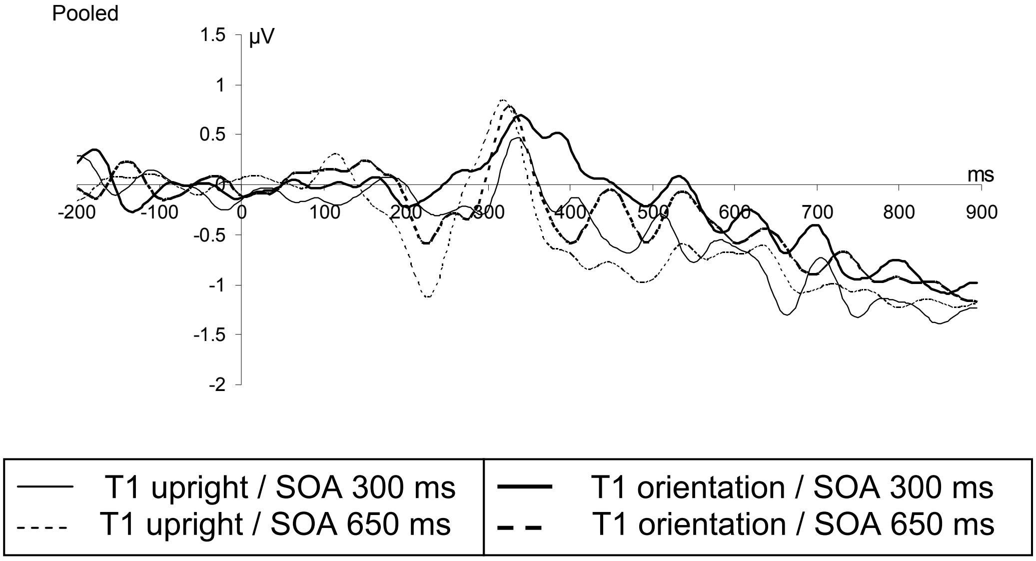

Figure 4.4. N2pc and SPCN stimulus locked to T2, for the four different conditions: S1 0º / 300 ms SOA; S1 0º / 650 ms SOA; S1 140º / 300 ms SOA; S1 140º / 650 ms SOA for the subtracted signals PO7 / PO8, P7 / P8, O1 / O2, PO3 / PO4, P3 / P4 and their pooled waveform. A 15 Hz filter was used on a waveform that started 200 ms before stimulus onset and ended 900 ms after stimulus onset. Thin lines represent S1 0º orientation, bold lines represent S1 140º orientation, straight lines represent short SOA and dotted lines represent long SOA.

SPCN onset latency

To test whether the SPCN onset latency was sensitive to S1 orientation and SOA we used a jackknife analysis (Kiesel et al., 2008; Miller et al., 1998; Ulrich & Miller, 2001). The onset latencies were submitted to an ANOVA with SOA and S1 orientation as within-subjects factors. The jackknife analysis confirmed what can be seen in Figure 4.4, namely that the SPCN onset was earliest for the S1 0°/650 ms SOA condition, then the S1 0°/300 ms SOA condition, then the S1 140°/650 ms SOA condition, followed later by the most centrally taxing condition, the S1 140°/300 ms SOA condition. This was reflected in the ANOVA by significant effects of S1 orientation, $F_{\text{adjusted}}(1, 11) = 6.4$, $MSE_{\text{adjusted}} = 53022.2$, $p < .05$, and SOA, $F_{\text{adjusted}}(1, 11) = 7.5$, $MSE_{\text{adjusted}} = 30286.3$, $p < .05$. There was no interaction between S1 orientation and SOA, $F_{\text{adjusted}} < 1$. This same pattern of statistical results was obtained when a lower threshold of -0.6 µV was used, suggesting that the results did not depend on a specific choice of analysis parameters.

A visual inspection of the waveforms shown in Figure 4.4 suggested that the SPCN component approached a similar amplitude for all conditions near the end of the analysis window, showing that by that time, information from all four conditions had been encoded into VSTM (Brisson & Jolicœur, 2007a). To examine this statistically, we computed the mean amplitude of the SPCN in a time window of 800–900 ms. There were no significant effects of S1 orientation, SOA, and electrode position *F*’s < 2.9, *p*’s > .10, except for a marginally significant interaction between SOA and electrode position, *F*(4, 44) = 2.6, *MSE* = 1.4, *p* < .10, with activation over the electrode pairs quite similar at the short SOA and more widespread at the long SOA, with a maximum activation over electrode pair P3 / P4.

Discussion

The present PRP study investigated whether mental rotation affects the progress of deploying visual-spatial attention in a concurrent task. Because mental rotation involves a variable duration of the same process it is capable of causing different degrees of dual-task interference with manipulation of other processes. Decisions about the position of gaps in S2 were strongly delayed if S1 required a mental rotation. This could be interpreted as showing that mental rotation occupied central processing capacity (Ruthruff et al., 1995; van Selst & Jolicœur, 1994), the same capacity that is used by response selection. However, an alternative interpretation to consider is that the dual-task interference was not caused by mental rotation but by response selection itself, which is contingent on rotation and is already known to produce a PRP effect. Likewise, the PRP effect on performance need not be attributed to interference with attentional processes, because T2 also involved response selection, which would be delayed as long as limited-capacity processes of T1 would be in progress.

More direct evidence for the bottleneck properties of mental rotation and attentional processes was obtained by an analysis of the ERPs. The N2pc was calculated to monitor enhanced processing contralateral relative to ipsilateral to the visual field containing a target. The N2pc has been validated as a real-time measure of the deployment of visual-spatial attention (Luck & Hillyard, 1994) and has successfully been applied to investigate attention in a PRP setting (Brisson & Jolicœur, 2007a; 2007b). The SPCN component, following the N2pc, is believed to index the storage of information in VSTM (Brisson & Jolicœur, 2007a; 2007b; Jolicœur et al., 2008; Vogel & Machizawa, 2004). Because attention and VSTM storage necessarily precede response selection, attenuation of the N2pc or a delay of the SPCN can not be attributed to dual-task interference on selection of R2. Instead, it has to be attributed to the attention processes as such.

The N2pc was attenuated when T2 was presented while subjects performed concurrent mental rotation, and the SPCN was significantly delayed. The attenuated N2pc showed that spatial attention could not be deployed efficiently to the lateralized target in the T2 display as long as limited-capacity processes engaged in T1 had not run to completion. Thus, the data replicate previous studies of Brisson and Jolicœur (2007a, 2007b) in showing that the process of attention shifting has bottleneck properties.

The role of mental rotation in dual-task interference is demonstrated most clearly by the near complete elimination of the N2pc at short SOA if S1 was tilted, and thus called for a mental rotation, as compared to a normally oriented S1 (Figures 4.3, 4.4). The main difference between these two types of trials is the duration of mental rotation, all else remaining constant – including deciding whether a character is in normal or mirrored version, and including response selection. The attenuation of the N2pc was observed 190-260 ms after T2, that is 490-560 ms after S1 on short SOAs. Given a mean RT of 857 ms to an upright and 1107 ms to a tilted S1, it is clear that the attenuation of the N2pc can only be attributed to response selection if the implausible assumption is made that response selection starts at least 547 ms before the response. The only remaining explanation is that there was direct interference of mental rotation onto the deployment of attention. To our knowledge this is the first demonstration of PRP interference in which response selection is neither the delaying, nor the delayed process. This demonstration shows that response selection is not a necessary ingredient of dual-task cost, which undermines the traditional response-selection bottleneck model (Pashler, 1994).

In contrast to the amplitude effects we observed for the N2pc, the effects on the SPCN can be interpreted as principally due to latency shifts. The convergence of the SPCN waveforms near the end of the measurement window for all four conditions is broadly consistent with the similar accuracy in T2 achieved in all conditions (between 89% and 92%). Most important, however, was the observation that the SPCN wave had different onset latencies in the different conditions (Figure 4.4), and in particular that the onset of the SPCN was the most delayed in the condition associated with the greatest PRP interference in the mean RT2s, namely the condition in which the SOA was short and S1 was rotated to 140°. There were also effects of orientation and SOA on SPCN amplitude in the fixed window of 380-500 ms, but these were a consequence of the latency shift.

Although these effects were quite substantial, and clearly statistically significant, the delays in SPCN onset cannot explain all of the observed differences in mean response times in T2. For the delay of T2 with increased task overlap (reduced SOA) we found a behavioural effect of 197 ms when S1 was upright and an effect of 292 ms when S1 was tilted. The found SPCN effect for SOA 300 ms versus SOA 650 ms was 98 ms when S1 was upright and 90 ms when S1 was in orientation. For the two SOAs, the SPCN latency effect was 49.5% and 30.8% of the behavioural effect respectively. It is likely, therefore, that additional delays of processing took place following entry into VSTM, likely at the response-selection stage.

Could our interpretation of the present results be compromised by issues of component overlap, given that our paradigm required the presentation of two stimuli in close temporal proximity? Two lines of argument allow us to exclude component overlap as a significant concern in this work. First, the main electrophysiological results of interest were derived from contralateral minus ipsilateral difference waves (N2pc, SPCN), that cancel out any electrical brain activity that is not lateralized systematically with respect to the side of presentation of T2 (see Brisson & Jolicœur, 2007a; Luck & Hillyard, 1994). Given that S1 was presented at the center of the screen and that the independent variables were manipulated orthogonally to the position of T2 in the visual field, S1-related electrical activity was equivalent in the contralateral and ipsilateral waveforms defined relative to the spatial position of T2, and thus this activity was entirely canceled out in the contralateral minus ipsilateral difference waves. Second, the N2pc was attenuated by mental rotation if considering only the trials at the long SOA. The fact that effects of orientation on the N2pc were observed even when SOA was held constant showed that mental rotation itself was capacity limited or shared capacity-limited processes with other processes. The observed differences cannot be due to differential component overlap but are purely due to differences in mental rotation.

The question remains what underlying cause can explain the interference between processes that do not seem to be related in terms of function or computational logic, and why these processes also interact with response selection. Our data are showing only that such interference occurs but not why, so we can only speculate. Let us first consider what might be the commonality among these three different processes that makes them sensitive to interference. One way to look at such processes is to consider them as computational routines that take parameters from control processes, as envisioned by ECTVA (Logan & Gordon, 2001), or other processes that provide the necessary control signals. Response selection processes identify and select an appropriate response *given* particular stimulus information; mental rotation processes modify the spatial characteristics of a particular stimulus representation *given* a particular rotation direction; and attentional processes facilitate the processing of stimulus information from a particular location *given* that this is where the target has been located. In other words, all three processes operate conditionally on particular input parameters. Whereas the processes themselves can be prepared in advance of the eventual presentation of stimuli, thus rendering them a kind of "prepared reflex" (cf., Hommel, 2000), their online parameterization may require capacity-demanding executive supervision (Logan & Gordon, 2001) or at least be typically accompanied by such supervision to avoid errors (Meyer & Kieras, 1997a, 1997b).

This poses the obvious next question of why the parameterization process may create a processing bottleneck. A possible answer is perhaps more obvious if one considers the way the parameterization process might be realized in the human brain. Conditioning the behavior of a computational routine to particular parameters is equivalent to creating a number of if-then-type associations between the neural representations of the parameters or conditions and the neural representations of the processes being launched as a function of these parameters or conditions. These associations may be hardwired, as in the case of highly overlearnt stimulus-response relations or habits, but often they will be soft-coded and implemented for present purposes only (cf., Monsell, 1996). Given that the to-be-related neural representations are likely to be active in different areas of the brain, linking them poses a kind of binding problem (Hommel, 1998), which calls for integration processes that span large distances in the brain. Even though we are far from understanding how neural integration works (for some considerations, see Engel & Singer, 2001; Raffone & Wolters, 2001; Von der Malsburg, 1999), it is clear that relating stimulus representations to response representations (as in the case of response selection), rotation operations to directional representations (as in the case of mental rotation), and stimulus features to locations (as in the case of shifting attention) are global operations connecting distant cortical maps.

Global operations are particularly sensitive to interference and noise from the activation of other, currently irrelevant neural codes, suggesting that potentially interfering neural activation is suppressed until the operation is completed. This is indeed suggested by the study of Gross et al. (2004), who used magnetoencephalography (MEG) to study the attentional blink (Raymond, Shapiro, & Arnell, 1992) — an effect that has also been suspected to have bottleneck characteristics (Jolicœur & Dell'Acqua, 2000). Gross and colleagues computed a measure of the amount of global communication in the brain that could be tracked over time. As it turned out, successful performance in the demanding attentional task was characterized by the increase of communication during the processing of a target and the sub-baseline decreases of communication in response to distractor stimuli. This suggests that establishing global cortical communication to serve one process or function may effectively prevent or inhibit global communication with respect to any other process or function (Hommel et al., 2006). This kind of functional bottleneck may not be restricted to response selection, mental rotation, and attention shifting but may be present with any cognitive operation that relies on global communication between cortically distributed neural codes. Accordingly, we suspect that mental rotation and attention shifting are only a few of many processes that exhibit bottleneck properties, if only sufficiently sensitive methods are employed to detect them.

Before closing we would like to note that it is remarkable that the N2pc variation was predominantly expressed in an amplitude effect rather than a latency effect, although latency effects have been observed in a number of previous studies (Brisson & Jolicœur, 2007a; 2007b; Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a; 2006b; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 2007). One could hypothesize that the relatively early cortical modulation of the visual input reflected in the N2pc requires a top-down signal within a critical time window. Brisson, Robitaille and Jolicœur (2007) investigated whether the N2pc was regulated top–down only or whether it was regulated top-down in combination with bottom-up processes. They varied stimulus intensity and measured the P1 as a measure of bottom-up perceptual processes and the N2pc. Results showed an expected amplitude increase for P1 with increasing intensity, but no amplitude effects for N2pc. The latency of the N2pc however, was affected with a later N2pc onset when the stimulus intensity was low. These results suggested that N2pc-amplitude effects are caused by top-down modulation and latency effects occurred as a result of delayed deployment of visual-spatial attention. More work will be required to understand, fully, why the N2pc is systematically attenuated by dual-task interference rather than simply delayed.

In conclusion, the present experiment shows that mental rotation and attention shifting to not only interact and interfere with response selection (e.g., Brisson & Jolicœur, 2007a), but that they also interfere with each other in a way that reveals their bottleneck properties. Mental rotation can influence the deployment of visual-spatial attention as well as delay the entrance of information into VSTM. Because the capacity-limited process of mental rotation - in contrast to response selection – varies linearly (with increasing angle to upright), we were able to systematically manipulate its duration. There is thus strong evidence that dual-task costs are not only created by response selection but by other, in this case earlier processes as well. It is possible that the same applies to any cognitive operation that requires the global integration of distributed neural codes, but this issue requires more research.

Chapter 5

Capacity Limitations of Cognitive Operations

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Manuscript in preparation

Abstract

Several models of dual-task performance attribute dual-task costs to a bottleneck in response selection. However, increasing evidence suggests that other processes can also have bottleneck characteristics. This led us to perform a more detailed process analysis. We combined a Psychological Refractory Period (PRP) paradigm including two mental rotation tasks with a working memory (WM) load task. Experiment 1 replicated earlier findings that performance on the first rotation task was facilitated if the response categories in the two rotation tasks matched, but only if the two tasks called for mental rotations going into the same direction—i.e., if the same directional parameter could be used for the two mental rotations. Interestingly, this interaction was not modulated by WM load, while the category-match effect was. Experiment 2 provided the opportunity to prepare for mental rotations in advance of stimulus presentation. Valid cues improved performance, suggesting that rotation parameters can be prepared in advance, but only if the two tasks required rotations into the same direction. Findings point to the parameterization of cognitive operations as one major bottleneck process in multitasking and to working memory as another, with the latter providing limited capacity for the storage of intermediate results of cognitive operations.

Introduction

Dual-tasking taxes a brain to such an extent that the tasks involved take longer than if they were conducted separately (e.g., Pashler, 1994). Research sought to account for this delay by disentangling processes that have distinct capacity-limited properties from those that can presumably be conducted in parallel without substantial costs. The Psychological Refractory Period (PRP) paradigm (Telford, 1931) turned out to be a helpful tool in this endeavor. It typically entails two stimuli (S1 and S2), which are presented shortly after each other and require speeded response (R1 and R2). S2 can be presented after a short or long delay, the stimulus onset asynchrony (SOA), thus causing a more or less pronounced overlap of the two tasks. A typical result is an increase in reaction time to S2 (RT2), and thus increased dual-task costs, with decreasing SOA (Pashler, 1994; Welford, 1967). A long research tradition that considered several steps of information processing converged on response selection as the main culprit in dualtasking, that is, as *the* bottleneck stage (see Pashler, 1994, for a review).

More recent studies provide a more complex picture, however. For one, stages preceding response selection proper have been demonstrated to possess bottleneck characteristics, such as mental rotation (Ruthruff, Miller, & Lachman, 1995; Van Selst & Jolicœur, 1994), short-term memory consolidation (Jolicœur & Dell'Acqua, 1998), and memory retrieval (Carrier & Pashler, 1995). For another, response selection itself seems to fall into several subprocesses with some but not all functioning as a bottleneck. For instance, while the checking of activations of response representations and the selection of one for execution seems to have bottleneck properties, the translation of stimulus evidence into the activation of response representations does not (Hommel, 1998; Logan & Gordon, 2001). These observations suggest that the real understanding of the limits of dualtasking requires analyses at a finer-grained level than suggested by the traditional distinction between perceptual processing, response selection, and response execution. As we will argue, it is possible that any cognitive operation can exhibit bottleneck characteristics if the tasks involved require these operations to be run in different modes or with different parameters.

In the present study, we aimed at analyzing the processing characteristics of cognitive operations involved in stimulus-response translation (in Experiment 2) and in what has come to be known as mental rotation (Band & Miller, 1997; Van Selst & Jolicœur, 1994; Shepard & Metzler, 1971; Experiment 1). In a mental rotation task, people judge stimuli that are rotated away from their normal upright position, such as letters tilted to different degrees. While identification is often unaffected, judging whether stimuli are normally oriented or mirror reversed is very difficult, as shown in long RTs (Van Selst & Jolicœur, 1994). Interestingly, the RT needed to make such judgments varies with the degree of tilting, suggesting that people may “mentally rotate” the internal stimulus representation to its normal upright position, taking more time the more the stimulus deviates from that position (Corballis, 1986; Cooper, 1976). The hypothetical rotation process has been found to delay other tasks, and the response-selection processes of these tasks in particular, just like response selection does (Pashler, 2000). This raises the question why it does so and what the commonality with response selection may be. One possibility is that mental rotation and response selection may both involve cognitive operations that need to be conditionalized or parameterized (much like attentional operation mechanisms in the model of Logan & Gordon, 2001) in one way or another, so that they can accept only one parameter at a time. With respect to response selection, Logan and Schulkind (2000) found evidence for parallel stimulus-response translation if the same task rules could be applied to S1 and S2 but not if different rules were necessary—an observation we will get back to in Experiment 2. With respect to mental rotation, one may argue that the rotation operation needs to be parameterized differently for clockwise and counterclockwise rotations, which would suggest that multiple stimuli can share the same operation (i.e., be treated according to the same rule) if this implies the same rotation direction but not if different directions are needed.

Indeed, Pannebakker, Band, and Ridderinkhof (2009) obtained findings supporting this idea. In a PRP design, they presented tilted stimuli as S1 and S2 and manipulated the direction of the tilting. There is evidence that people mentally rotate stimuli along the shortest path, so that stimuli tilted up to 180° counterclockwise from their normal upright position are mentally rotated clockwise whereas clockwise tilted stimuli are mentally rotated counterclockwise (Cooper, 1976). Pannebakker et al. (2009) observed that the reaction time on the first task (RT1) was shorter if S1 and S2 fell into the same category, that is, if they were both normally oriented or both mirror reversed (the category-match effect). However, this effect was only present if the two stimuli differed from normal upright in the same way, that is, if S1 and S2 were both tilted clockwise or both tilted counterclockwise.

This suggests the following scenario: If two stimulus representations are in need of the same kind of “mental correction” by either a clockwise- or counterclockwise-parameterized cognitive rotation operation, they can perform this operation in parallel. Once they are rotated back to the normal upright they are categorized as normally oriented or mirror reversed in parallel and activate corresponding category representations. If these representations are incompatible (i.e., if one stimulus is normally oriented and the other is reversed) conflict arises and performance suffers in comparison with compatible representations. However, if two stimulus representations need to be mentally rotated in opposing directions, implying different parameters for the rotation operation, only one stimulus can be further processed at the time. As this is likely to be the earlier presented S1, S2 will need to wait until the mental rotation of S1 is completed; so that it will be too late for S2 and the category representation it will activate to affect S1 processing. Hence, no category-match effect occurs with incompatible mental rotations.

Match effects due to crosstalk are reflected not only in RT1, but also in RT2. However, RT1 match effects form a more reliable measure of crosstalk than RT2 match effects. RT2 match effects are confounded with response repetition effects, which can occur even in the absence of parallel rotation and crosstalk. Therefore, RT2 match effects can only serve as converging evidence for crosstalk, whereas RT1 match effects are direct evidence for crosstalk.

Experiment 1

In the first experiment of the present study, we attempted to further investigate and characterize the possible capacity limitations of cognitive operations involved in mental rotation. The evidence of Pannebakker et al. (2009) that operations can be used for more than one cognitive code at a time rules out the most severe limitations one may consider but it by no means shows that capacity limitations do not exist. In many tasks and real-life dual-tasking situations working memory (WM) is more heavily taxed than in studies like those of Pannebakker et al. (2009), so that we were interested to see how WM load may affect the mental rotation process.

As indicated in Figure 5.1, we considered two types of effects. According to our hypothesis, the rotation process can take only one direction parameter at one time, thus programming either a clockwise or a counterclockwise rotation. Mutually inhibitory links between rotation processes allow for only one operation to be active at any one time. With low load, more than one stimulus code has access to the rotation process, so that multiple codes can be rotated in the same direction at the same time.

Once the rotation is completed the orientation of the stimulus can be determined and the appropriate response-category code (belonging to either normally oriented or mirror reversed) be activated. For one, a higher load may reduce the number of stimulus codes that can be “mentally rotated” at a time. This would suggest that low load would yield the same outcome as obtained by Pannebakker et al. (2009), showing that performance on the first task is facilitated by matching categories, but only with compatible rotations. With high load, however, even compatible rotations may not allow for the rotation of more than one stimulus code at the time, so that the interaction between rotation compatibility and category match would break down. In other words, load would be expected to interact with rotation compatibility and category match (hypothesis A; see also HA Figure 5.1).

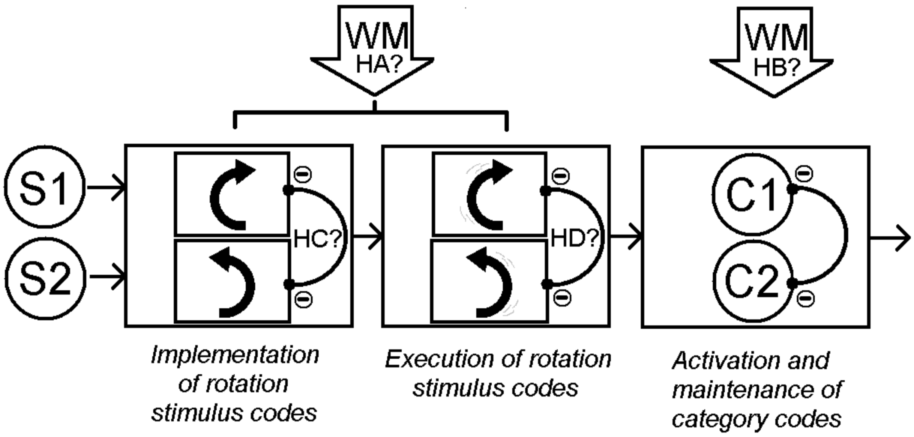

Figure 5.1. Schematic representation of the different subprocesses (i.e. rotation, category code activation) and their relation with working memory (WM). Two stimuli are entered into the model and subsequently need clockwise or counterclockwise rotation (represented by the rotating arrows inside the first box) before they can be distinguished as mirror and normal oriented and be maintained in WM accordingly. The line linking the two rotation boxes in the first and second main box represents the mutually inhibitory links that allows for only one operation to be executed at the time. HC and HD refer to the hypotheses that place the mutually inhibitory links either in the first main box that represents the rotation-implementation phase or in the second main box that represents the rotation-execution phase. We investigated whether WM (represented by the large arrows above both the two boxed processes) is involved during rotation (implementation and execution; HA) and / or activation and maintenance (HB).

Another possibility is that load does not affect the rotation process proper. As observed by Hommel (1998), multiple stimuli seem to activate response codes in parallel, consistent with our assumption that cognitive operations are not (tightly) limited in capacity. Interestingly, WM did not affect the indication of parallel processing in the study of Hommel and Eglau (2002), where participants carried out a PRP task while holding sets of items in memory that varied in size.

Ellenbogen and Meiran (2008) provided evidence that increasing set sizes beyond the four items used by Hommel and Eglau (2002) does reduce indications for parallel processing. However, capacity limitations demonstrated by Ellenbogen and

Meiran (2008) may apply to the maintenance of the results of cognitive operations but not the operations themselves. This implication can be explained by the following logic. Operations produce outcomes, that is, they activate a code other than the stimulus, a code that represents the result of the operation. In the case of mental rotation, they produce a visual code representing the rotated-to-upright stimulus and a related code corresponding to the orientation of the stimulus, which we call the orientation-category code. If these codes are not maintained for some minimal time but decay right away, they are unlikely to impact processing, which would eliminate the category-match effect. It is not unreasonable to assume that higher WM load impaired maintenance, which after all may be considered a function of WM, so that the category-match effect is reduced or disappears with higher WM load (hypothesis B; see also HB Figure 5.1).

In Experiment 1, we combined the design of Pannebakker et al. (2009) with a WM task adopted from De Fockert, Rees, Frith, and Lavie (2001). With low memory load, we expected to replicate the findings of Pannebakker et al. (2009) and in particular the interaction between rotation compatibility and category match. The interesting question was whether the same pattern (rotation compatibility × category match) would be obtained under high load, which would suggest that WM does not (strongly) affect the rotation operation. This would reject hypothesis A (HA in Figure 5.1) in which is suggested that WM does have an effect on the rotation process. In addition to that, we were interested to see whether the category-match effect would be reduced or eliminated under the high-load condition, which would suggest that the activation and/or maintenance of codes representing the orientation of the stimuli would suffer from high load (Hypothesis B; HB in Figure 5.1).

Methods

Participants

Twenty-one students (3 male; 3 left-handed) of Leiden University aged between 18 and 30 (mean age: 19.6 years) participated in this experiment that took two sessions of one hour each. The experiment was conducted in accordance with relevant laws and institutional guidelines and was approved by the local ethics committee from the Faculty of Social Sciences. All students had normal or corrected to normal eye-sight. They received either 10 Euro or course credits or a comparable combination of both.

Apparatus

Participants were tested individually, in separate booths in the Cognitive Psychology Lab. The booth was dimly lit, and participants were sitting in front of a 17 inch computer screen with a viewing distance of approximately 75 cm. Responses were made with key-presses on the bottom row keys of the computer keyboard; the left hand operating the z- and x-button and the right hand operating the n- and m-button of a QWERTY keyboard.

Stimuli

In the PRP task the letters f, G, k, Q and R served as S1 and S2. These stimuli were selected because their asymmetry allows the creation of unambiguous rotation and mirroring conditions. They were oriented either normally or mirror-imaged and their orientation was 120 degrees. Clockwise and counterclockwise tilted stimuli occurred equally often. The characters were presented in black on a white screen within a black-lined rectangle. As this was a dual task, two characters were presented within the rectangle with a visual angle of 5.8º × 3.6º (horizontal × vertical). Stimuli were presented well within the boundaries of this rectangle. The two presented stimuli were separated by a SOA of 100 or 800 ms. SOA, mirror/normal image of letters, response category match/mismatch and rotation direction were all varied randomly within blocks. S1 always appeared left from the middle and called for a left-hand response, S2 always appeared right from the middle and called for a right-hand response. The mapping of normal/mirror image to index/middle fingers was balanced between subjects. A normal image required either the left finger (‘z’ or ‘n’ key) or the outer finger of each hand (‘z’ or ‘m’ key). A mirror image required either the right finger (‘x’ or ‘m’ key) or the inner finger of each hand (‘x’ or ‘n’). Thus, the category-match effect was not confounded with the benefit of using homologous fingers. For the WM task, the digits 0, 1, 2, 3, and 4 were presented at the beginning of each trial. At the end of the trial, a key (1-4) on the keyboard had to be pressed as a test of recall.

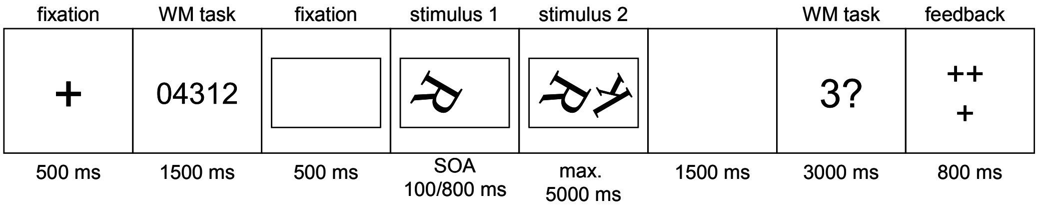

Figure 5.2. Sequence of events within one trial in Experiment 1: A PRP paradigm containing two rotated letters in the centre of the screen during which a WM load has to be maintained active

Procedure

Before the start of the experiment, participants received a written instruction. They were asked to respond as quickly as possible, and not to be too cautious. No instruction was given as to which stimulus to respond first. Then more explanation was presented on the computer followed by four practice blocks, after which the experimental blocks started. The first practice block was a single-task practice for the left hand, and the second one was a single-task practice block for the right hand. These two blocks contained 20 trials each. The third block was a dual-task block session that consisted of 20 trials. In the last practice block containing another 20 trials, the additional task was added.

Experimental trials were presented in ten blocks of 64 trials. Pauses separated the blocks and participants were encouraged to use them. Within the experimental blocks, the trial started with the presentation of a fixation cross in the middle of the screen for 500 ms (see Figure 5.2). Then, the five digits of the WM task were presented for 1500ms, either in an easy (01234) or in a difficult (e.g. 03421, 02431) order. Note that the zero is always the first digit. Next, a rectangular fixation appeared on the screen again for 500 ms after which S1 appeared left of the middle of the screen. After a variable SOA S2 appeared next to S1 and stayed on the screen until response or 8000 ms, whichever came first. After R2 and a 1500 ms blank, one digit (1-4) and a question mark appeared on the screen for 3000 ms. Participants were required to press the key corresponding to the digit that had followed that same digit in the digit-line-up at the beginning of the trial. Feedback was then presented on the screen for 800 ms. A correct response resulted in a ‘+’ feedback response, while an incorrect response elicited a ‘-’ feedback response. The first and second stimulus of the main task were presented left and right from the middle respectively, while the WM task was presented below the middle. After a response-stimulus interval of 1000 ms a fixation cross appeared to announce the beginning of the next trial. At the end of each block, an average RT in ms and a percentage correct (PC) over that block was presented to give participants insight on their progress, and to motivate them to keep trying to respond faster on every block.

Results

RTs longer than 5000 ms or shorter than 150 ms and trials in which R2 preceded R1 were excluded from the analysis of RT and PC. Mean RTs were based on trials with a correct response to both stimuli. Data were analyzed with repeated measures analysis of variance (ANOVA) using a 2 × 2 × 2 × 2 design with the within-subjects factors rotation compatibility, category match, SOA and WM-load. Alpha was set at 0.05.

RT1

Of the main effects, only the effect of SOA was significant, *F*(1,20) = 24.6, *MSE* = 58909, *p* < .001. RT1 was 132 ms faster when the two stimuli in the PRP task were more temporally separated. The key interaction between rotation compatibility and category match was also significant, *F*(1,20) = 8.9, *MSE* = 4721, *p* < .01 (see Figure 5.3). Follow-up analyses showed that the category-match effect was substantial for compatible rotations (39 ms), *t*(20) = 2.3, *SEM* = 68, *p* < .05, but not significant for incompatible rotations (6 ms), *t*(20) = .37, *SEM* = 62, *p* = .713. The interaction of category match and SOA showed that the match effect decreased with increasing SOA from 35 ms to 2 ms, *F*(1,20) = 8.2, *MSE* = 3518, *p* < .01 (see Figure 5.4). The interaction effect of category match and WM load was significant, *F*(1,20) = 8.6, *MSE* = 2869, *p* < .01 (see Figure 5.5). At low WM load, the category-match effect was 19 ms while in high WM load trials the category-match effect was virtually absent (3 ms). The pivotal three-way interaction between WM load, rotation compatibility, and category match was far from significant, *F*(1,20) = .43, *MSE* = 4745, *p* = .519, indicating that WM load did not influence the otherwise significant interaction between rotation compatibility and category match.

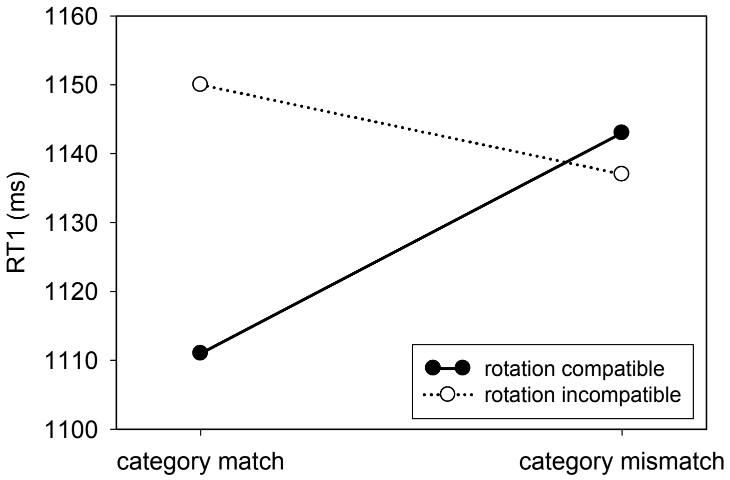

Figure 5.3. The interaction of rotation compatibility and category match on reaction time 1 of Experiment 1

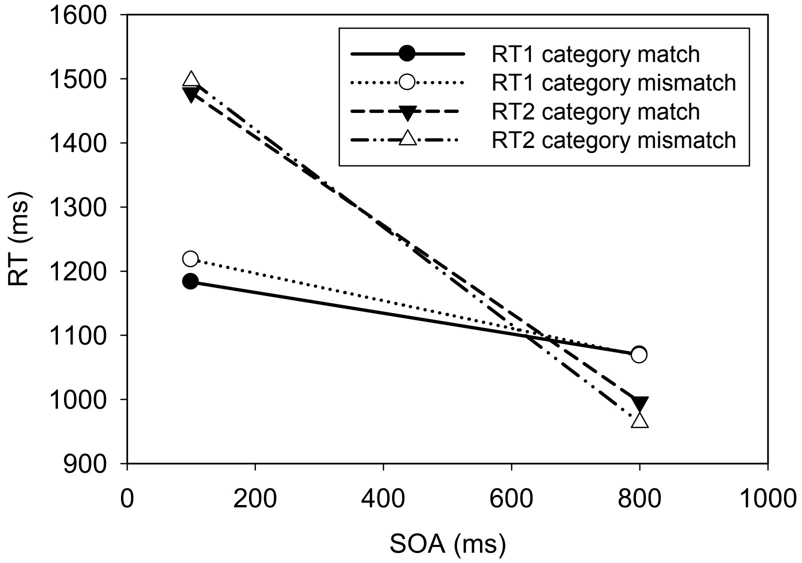

Figure 5.4. The interaction of category match and SOA on reaction time 1 and 2 of Experiment 1

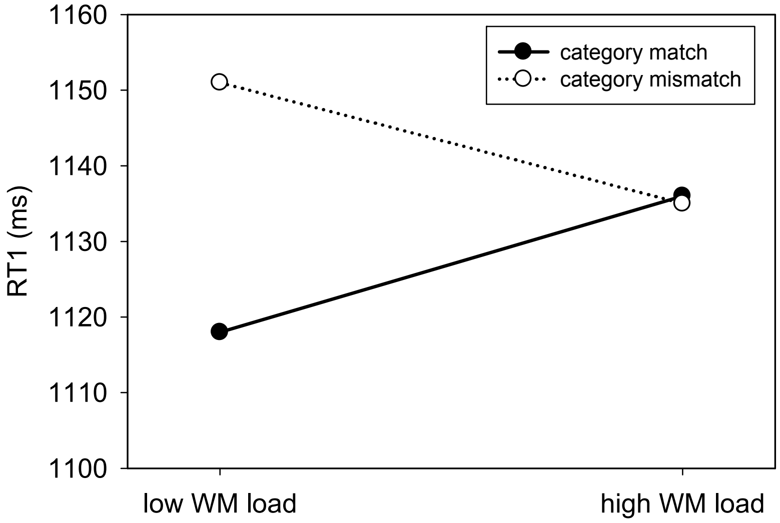

Figure 5.5. The interaction of category match and WM load on reaction time 1 in Experiment 1

PC1

Only the main effect of WM load was significant, *F*(1,20) = 7.0, *MSE* = 64, *p* < .05, indicating that higher WM load resulted in a 2.3% increase in errors in response to S1.

RT2

The main effects of rotation compatibility, *F*(1,20) = 8.2, *MSE* = 6057, *p* < .05, and SOA were significant *F*(1,20) = 174.9, *MSE* = 124128, *p* < .001. RT2 was 24 ms shorter to compatible than to incompatible rotations and 508 ms longer to short than to long SOA. The interaction of rotation compatibility and category match was significant, *F*(1,20) = 9.2, *MSE* = 8456, *p* < .01: the match effect was more pronounced when rotations were compatible (38 ms) than when they were incompatible (23 ms). The interaction of category match and SOA, *F*(1,20) = 8.3, *MSE* = 6316, *p* < .01, (see Figure 5.4) showed a reduction of the category-match effect from 32 to 17 ms with increasing SOA. The interaction of SOA and WM load was due to a larger effect of WM load with the short (31 ms) than with the long SOA (-14 ms), *F*(1,20) = 4.7, *MSE* = 8731, *p* < .05. The three-way interaction effect of WM load, rotation compatibility, and category match was again not significant, *F*(1,20) = .58, *MSE* = 3512, *p* = .456.

PC2

Two main effects were significant: category match, *F*(1,20) = 8.5, *MSE* = 41, *p* < .01, and WM load, *F*(1,20) = 6.1, *MSE* = 69, *p* < .05. PC2 was slightly higher (2.1%) when the categories mismatched than when they matched, and PC2 decreased with increasing WM load (2.3%). No other effects were significant.

WM task

Performance in the WM task did not vary with the other tasks. The only significant effects were an increase of RT with an increased WM load by 306 ms, *F*(1,20) = 57.41, *MSE* = 137147, *p* < .001, and a decrease of PC by 2.6%, *F*(1,20) = 8.4, *MSE* = 65, *p* < .01.

Discussion

The results show that we were able to replicate the observation of Pannebakker et al. (2009) that the category-match effect impacts the first task only if S1 and S2 are tilted into the same direction and thus call for the same kind of “mental rotation”. As we have argued, this suggests that more than one stimulus code can be rotated at a time but only if the same rotation operation can be applied to all codes in question. If not, codes needing a different rotation have to wait until the ongoing rotation is completed, so that only one category code is activated at a time and conflict between category codes does not occur early enough to affect RT1.

Importantly, there was not any evidence that the crucial interactions between rotation compatibility and category match might be mediated by WM load, suggesting that the number of stimulus codes undergoing mental rotation is not limited by WM capacity, rejecting hypothesis A (see also Figure 5.1). However, we did obtain an interaction between the category-match effect and WM load. This suggests that category codes are activated to a lesser degree, the higher the WM load, presumably because the activated codes of the memorized stimuli interfere with the category codes, confirming hypothesis B (see also Figure 5.1). This means that WM storage capacity is not shared or needed by a cognitive operation like mental rotation as such but is necessary to encode and maintain the intermediate results these operations produce. A similar conclusion is suggested by a recent study of Ellenbogen and Meiran (2008), who used a PRP task in which one stimulus, a letter, was presented in a particular color. The stimuli could be presented in six different colors that required response to their individual color (six categories) or to their hue (two categories). Task 1 required a manual left-right response to the stimulus color and Task 2 required a vocal response (“red” or “green”; R2) to the stimulus color. R1 facilitation when responses matched color categories would suggest crosstalk. Results showed crosstalk if the six colors were mapped onto two responses but not if the six colors were responded to individually, suggesting that crosstalk occurs if the rule or category is activated. The number of activated rules is not limited, in line with the suggestion that rule activation does not require WM but its products do.

Experiment 2

Experiment 1 helped to specify the processing and resource limitations of cognitive operations. The same operation can apparently be applied to multiple stimuli but two versions of the same operation cannot be run under different parameter settings, such as different rotation directions. However, even though this conclusion fits with the observations of Pannebakker et al. (2009), raises the next question, whether people are reluctant or unable to *implement* an operation that is incompatible with the one in action or whether they do not *execute* incompatible operations concurrently.

The parameterization scenario suggests that there is only one “copy” of a given operation, so that changing a parameter is only possible after processes requiring another parameter are completed. In other words, the same operation cannot be implemented with different parameters at the same time. Another possibility is that implementing the same operation with different parameters is possible but only one operation can be executed at a time. That is, the mutually inhibitory links between the two operations shown in Figure 5.1 may refer to the implementation – represented by the first main box – or the execution – represented by the second main box – of the same type of operation.

In Experiment 2, we aimed at disentangling these two possibilities. The rationale was to dissociate the time point of implementing and of executing mental rotation processes. In Experiment 1, it was the stimuli that indicated whether a mental rotation would need to be rotated clockwise or counterclockwise. That is, the presentation of the stimulus was likely to be the trigger for both the implementation and the execution of the rotation operation. In Experiment 2, however, a cue indicated in which direction S2 should be rotated. The cue was presented prior to S1 and S2, in the same location as S2, and validly predicted the orientation of S2 in 75% of the cases. Thus, the design allowed for the implementation of mental rotation before the stimulus was presented, whereas execution of mental rotation would have to wait for the presentation of S2. The tasks were in other respects the same as in Experiment 1, except that no memory set was presented in Experiment 2.

Given the early presentation and the high validity of the cue, we assumed that participants would use it to parameterize the cognitive operations required for processing S2—if that is possible. Hence, if the main limitation in the rotation task is that the same operation cannot be *implemented* with different parameters at the same time (hypothesis C; see also HC in Figure 5.1), we would expect an effect of cue validity on RT2: a valid cue would permit the advance implementation and parameterization of correct S2 operations, while the invalid cue would not. Additionally, the validity effect on RT2 would not be restricted to compatible rotations, given that implementation of the incompatible rotation for task 2 could take place before S1 was presented. We would further expect an interaction between rotation compatibility, category match, and cue validity on RT1: with a valid cue a category match would backward-prime responses not only in rotation-compatible situations (as in Pannebakker et al., 2009) but also in rotation-incompatible situations.

If, on the other hand, there would be the limitation that only one operation can be *executed* at a time, then the cue-validity effect on RT2 should be absent (hypothesis D; see also HD in Figure 5.1). That is because, even if cues could be used for implementing the S2 rotation, this benefit would be lost due to inhibition by competing Task 1 processes.

Methods

Methods were similar as in Experiment 1, unless stated otherwise.

Participants

Thirty-one students (11 male; all right-handed) of Leiden University aged between 18 and 29 (mean age: 20.5 years) participated in this experiment. They received either five euros or course credits or a comparable combination of both. Three people were omitted from data-analysis because there performance did not rise above chance (50%) in one or more of the conditions.

Stimuli

The same fixation, stimuli, SOAs and response mappings were used as in Experiment 1. Before S1 presentation, a cue was presented at the location of S2, and its orientation was a valid predictor of S2 orientation in 75% of the trials. The cue was a white rectangle with a black lining with the same length and overall approximately the same size as the stimuli. Rotation compatibility, category match, SOA and cue validity were all varied randomly within blocks.

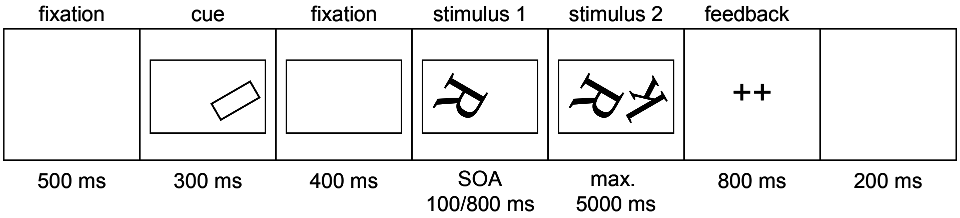

Figure 5.6. Sequence of events within one trial in Experiment 2: The cue is a rectangle that makes a valid prediction of the orientation of the second stimulus in 75% of the trials

Procedure

Before the start of the experiment, participants received a verbal instruction. They were asked to respond as quickly as possible, and not to be too cautious in their response. The predictive value of the cue for the second stimulus was explained. No reference was given as to which stimulus needed the first response. Subsequently, more explanation was presented on the computer followed by three practice blocks, after which the experimental blocks started. The first practice block was a single-task practice for the left hand, and the second one was a single-task practice block for the right hand. The third block was a dual-task block session. These three blocks contained 20 trials each.

Experimental trials were presented in 12 blocks of 54 trials. Pauses separated the blocks and participants were encouraged to use them. Within the experimental blocks, the trial started with the presentation of a fixation rectangle for 500 ms in the middle of the screen (see Figure 5.6). Then, the cue appeared for 300 ms within the fixation rectangle at the S2 location, followed by a 400 ms fixation rectangle only. Next, S1 appeared left from the centre of the screen inside the fixation rectangle, and after a variable SOA, S2 appeared next to S1 right from the centre of the screen, also inside the fixation rectangle. After the responses, a response-stimulus interval of 200 ms was presented before the fixation rectangle appeared to announce the beginning of the next trial.

Results and discussion

ANOVAs were conducted using a 2 × 2 × 2 × 2 design with the within-subjects factors rotation compatibility, category match, SOA, and cue validity.

RT1

Three of the four main effects were significant. Responses were 33 ms faster with compatible than with incompatible rotations, $F(1,27) = 13.8$, $MSE = 9074$, $p < .01$, 33 ms faster with matching than with mismatching categories, $F(1,27) = 5.1$, $MSE = 24581$, $p < .05$, and 153 ms faster with the longer than with the short SOA, $F(1,27) = 28.4$, $MSE = 91520$, $p < .001$. The interaction between rotation compatibility and category match approached but did not reach significance, $F(1,27) = 3.5$, $MSE = 7358$, $p = .071$ (see Figure 5.7): RT1 was shorter when the category responses matched compared to when they mismatched, but only significantly so in the rotation compatible condition with a significant match-effect size of 51 ms, $t(27) = 2.6$, $SEM = 18$, $p < .05$. This is in line with the parameterization scenario that holds that it is the implementation that keeps people from processing two stimuli that require concurrent mental rotation. Two-tailed paired samples t-tests showed a significant difference of 49 ms between rotation compatible and rotation-incompatible trials when the categories match, $t(27) = 3.4$, $SEM = 14$, $p < .01$, but only a marginally significant difference of 18 ms when the categories mismatch, $t(27) = 1.9$, $SEM = 10$, $p = .071$.

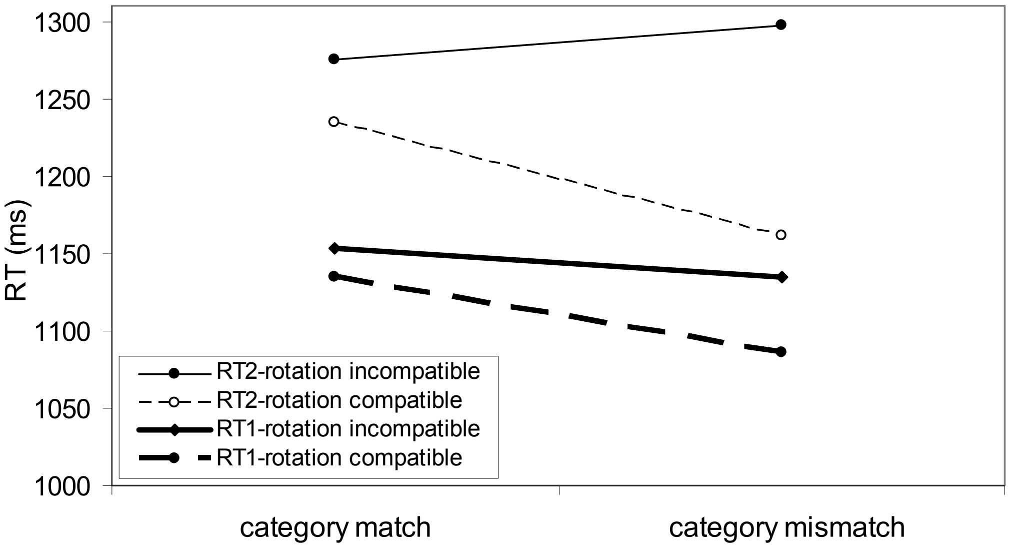

Figure 5.7. The interaction of rotation compatibility and category match on reaction time 1 & 2 of Experiment 2

The interaction between rotation compatibility and cue validity was also significant, *F*(1,27) = 8.7, *MSE* = 3343, *p* < .01: Rotation compatibility had a more pronounced effect with invalid than with valid cues (see Figure 5.8). Expressed differently, rotation-compatible trials showed shorter RT1 than rotation- incompatible trials for trials with an invalid cue (50 ms), *t*(27) = 4.1, *SEM* = 12, *p* < .001, and a marginally shorter RT1 (18 ms) for trials with a valid cue, *t*(27) = 2.0, *SEM* = 9, *p* = .054.

Additionally, the cue-validity effect was significant for rotation-compatible trials, *t*(27) = 2.5, *SEM* = 9, *p* < .05, with a shorter RT1 (23 ms) for the invalid cue compared to the valid cue. This interaction suggests the following: Task 2 direction information primed S1 rotation on the basis of the cue (early) and S2 (late). For both valid and invalid conditions, late direction information was compatible with S1 rotation and primed RT1. However, because in the invalid cue condition late direction information deviated from early information, it entailed a stronger re-implementation, and in consequence more facilitation on RT1 than in the valid cue condition, where late direction information only confirmed what was already represented. The cue-validity effect showed a reversed pattern for rotation incompatible trials, with a 9 ms longer

RT1 for the invalid cue compared to the valid cue, but this effect was not significant, *t*(27) = 0.89, *SEM* = 10, *p* = .383.

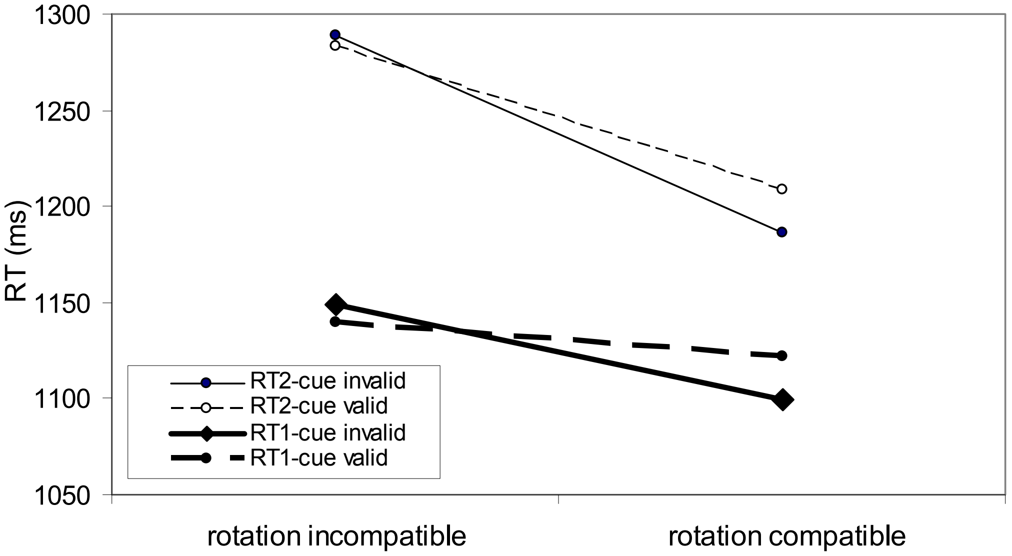

Figure 5.8. The interaction of rotation compatibility and cue validity on reaction time 1 & 2 of Experiment 2

Furthermore, the interaction between category match and SOA was significant, *F*(1,27) = 7.5, *MSE* = 5742, *p* < .05. As expected, the difference between category match and category mismatch was larger at a short SOA (53 ms) than for the long SOA (14 ms), *t*(27) = 3.1, *SEM* = 17, *p* < .01. A similar trend was found for rotation compatibility × SOA, which also showed a larger difference between category match and category mismatch at short SOA (50 ms) compared to long SOA (17 ms), *F*(1,27) = 3.5, *MSE* = 8956, *p* = .073. These two interactions are both evidence for crosstalk.

One three-way interaction was found between rotation compatibility × category match × SOA, *F*(1,27) = 5.5, *MSE* = 4727, *p* < .05. At the short SOA, the category match × rotation compatibility interaction resembled the outcome of the two-way interaction effect: there was only a benefit of 83 ms for category match when the rotations were compatible as well, *t*(27) = 4.0, *SEM* = 21, *p* < .001. At the long SOA, however, there was no significant match effect on compatible trials, *t*(27) = 0.6, *SEM* = 22, *p* = .536.

PC1

Results showed a significant main effect of cue validity, *F*(1,27) = 493.9, *MSE* = 21, *p* < .001. When the cue was valid, people were 10% faster than when the cue was invalid (91% versus 81%).

The only other significant effect was category match × SOA × cue validity, *F*(1,27) = 5.2, *MSE* = 22, *p* < .05. Performance was marginally better (1.2%) for category match than for category mismatch trials at short SOA and valid cues, *t*(27) = 1.8, *SEM* = 1, *p* = .082.

RT2

The main effect for SOA was significant, *F*(1,27) = 1014.2, *MSE* = 38485, *p* < .001. As expected, trials showed decreased RT2 (590 ms) with increasing SOA. RT2 was decreased with 89 ms in rotation-compatible trials compared to rotation-incompatible trials, *F*(1,27) = 76.5, *MSE* = 11531, *p* < .001. Similarly (but not significantly), RT2 was decreased with 26 ms in category-match trials compared to category-mismatch trials, *F*(1,27) = 2.1, *MSE* = 36631, *p* = .159.

The interaction between rotation compatibility and category match was significant, *F*(1,27) = 20.6, *MSE* = 12231, *p* < .001 (see Figure 5.7). Two-sided paired samples t-test showed a significant difference of 136 ms between category match and category mismatch only when the rotations were compatible, *t*(27) = 3.6, *SEM* = 20, *p* < .01. This effect was similar to the effect found at RT1.

The interaction between rotation compatibility and cue validity was also significant, *F*(1,27) = 5.1, *MSE* = 4353, *p* < .05 (see Figure 5.8). This interaction is similar to that measured at RT1, and requires a similar interpretation. RT2 was shorter when rotations were compatible. Valid cues differed significantly from invalid cues only at rotation-compatible trials, where RT2 was 23 ms longer for valid cues, *t*(27) = 2.7, *SEM* = 8, *p* < .05.

The interaction between category match and SOA was significant, *F*(1,27) = 20.4, *MSE* = 5947, *p* < .001. There was a match effect (59 ms) at the short SOA, *t*(27) = 2.8, *SEM* = 21, *p* < .05, but not significantly at the long SOA.

One three-way interaction was found between rotation compatibility, category match, and SOA, *F*(1,27) = 4.7, *MSE* = 6519, *p* < .05. At the short SOA, but not at the long SOA, there was a match effect (123 ms) with compatible rotations, *t*(27) = 5.2, *SEM* = 24, *p* < .001. No significant match effects were found with incompatible rotations on the short SOA level, but at the long SOA when the rotations were incompatible, category match trials were with 38 ms marginally slower than category mismatch trials, *t*(27) = 1.7, *SEM* = 22, *p* = .095.

PC2

The percentage correct for the second task showed main effects of rotation compatibility, *F*(1,27) = 38.3, *MSE* = 29, *p* < .001 and category match, *F*(1,27) = 13.7, *MSE* = 74, *p* < .001. Performance increased by 3.1% in case of compatible rotations compared to incompatible rotations and decreased by 3.0% in case of matching categories compared to when the categories mismatched. Furthermore, trials with valid cues showed a 9.1% higher performance than trials with invalid cues, *F*(1,27) = 241.6, *MSE* = 38, *p* < .001.

There was a marginally significant interaction between rotation compatibility and category match, *F*(1,27) = 4.1, *MSE* = 72, *p* = .053. Category mismatch showed a 4.6% higher performance than category match for rotation-incompatible trials, *t*(27) = 3.7, *SEM* = 1, *p* < .01.

The interaction between category match and SOA was significant, *F*(1,27) = 6.0, *MSE* = 25, *p* < .05. There was a regular match effect (4.2%) for the long SOA, *t*(27) = 4.1, *SEM* = 1, *p* < .001, but a reversed match effect (-1.8%) for the short SOA, *t*(27) = 2.2, *SEM* = 1, *p* < .05. These outcomes have the opposite pattern of the RT2 effects and point to a speed-accuracy trade-off.

The second experiment investigated whether pre-information about the rotation of S2 would allow for the advance implementation of S2-related rotation operations. If the cue was *valid*, the parameterization would already be in place long before S2 presentation. With the parameterization already installed, further processing of S2 could go straight through to the execution of the operation. This expectation – as put forward in hypothesis D (see also Figure 5.1) – was indeed confirmed by the interaction between cue validity and rotation compatibility. If the cue was *invalid*, the parameterization would need to be redone, at a moment when the parameterization of T1 was still ongoing. This required reactivation of the parameterization of T2. In that case, T2 codes were more active than when the cue was valid – in which case T2 codes had time to decay – which explains why during rotation-compatible trials the invalid cue resulted in a faster response than the valid cue.

Based on these observations, we would suggest that dual-task performance impairments related to rotation can be subdivided into implementation costs and execution costs. When a valid cue is presented early enough, implementation can take place already and thus does not contribute to performance costs. Although we found implementing the same operation with different parameters to be possible; only one operation could be executed at the time. Therefore, presenting cue 2 prior to S1 can facilitate RT only when the rotations are compatible, i.e., when only one operation is used. When the rotation directions differ, the mutually inhibitory links between the two operations would make it impossible to keep the cue information active during S1 rotation.

General discussion

In the current two experiments, we tried to specify the role of WM in dual-task processing and how it relates to the occurring delays. Thereto we investigated whether crosstalk was dependent on WM load (Experiment 1) and how it was related to implementation processes and execution processes (Experiment 2). In Experiment 1, we used two mental rotation tasks in a PRP paradigm with an additional WM task to investigate whether an increased WM load would influence crosstalk. WM load affected the category-match effect but not the interaction between category match and rotation compatibility. These results suggest that the items maintained in WM and the outcomes of the rotation operations of the PRP task compete for limited WM capacity. One parameterization / rotation can be applied to more than one stimulus, and during these processes crosstalk can occur. The subsequent maintenance of category codes does involve WM and is affected by the items maintained for the memory task.

In the second experiment, we further investigated the concept of crosstalk to see in which part of the processing crosstalk would occur. We divided the cognitive operation in a so-called implementation process and an execution process. We used a PRP paradigm with a mental rotation task for both tasks. The rotation direction of S2 was pre-cued by a tilted cue – valid on 75% of the trials – presented at the start of each trial. Cue validity did not yield a main effect, suggesting that cue information cannot be kept active during S1 rotation. Additionally, responses in rotation-compatible trials were faster than in rotation-incompatible trials for valid trials and even more so for invalid trials. This difference between validly and invalidly cued trials disappeared when rotations were incompatible. This suggests that only one rotation can be executed at the time, but implementing different parameters of the two rotations is possible.

Both experiments can be explained with a model depicted in Figure 5.1, in which the differentiation between rotation and category-code activation and their relation with WM are presented. WM operates on the activation and maintenance part and not on the category-code activation part where crosstalk takes place. This explains why in Experiment 1 we did not find a WM load effect by adding an additional task. The results in Experiment 2 confirm the separation between implementation and execution. Furthermore, they show that it is not the number of active parameters that is restricted, but the sort of operation that is being conducted. The mutually inhibitory links between the two operations refer to the execution of that operation.

The current experiments build on results presented by Hommel (1998) and Logan and Schulkind (2000). Contrary to earlier research (Pashler, 1984, 1994) that was focused primarily on response selection as the prime source of delays in dual tasks, they showed that it was necessary to separate response selection into more specific processes. Hommel (1998) showed that stimulus-response translation can be performed in parallel, but response decision making cannot. Logan and Schulkind compared crosstalk between similar and between different tasks, using the same stimuli (digits) in all tasks. They found evidence of crosstalk only when the tasks were similar. These results suggest that only when the same process was used for both tasks, a similar category-code activation (i.e., category match) could facilitate R1. Our research has shown that there is a difference between implementing (i.e., parameterization) and executing the rotation and that those processes have different restrictions. Earlier mental-rotation research showed the division of mental rotation into the mentally rotating the stimulus to upright and the following category decision (Corballis, 1986). But to our knowledge the distinction of implementation and execution of the mental rotation itself has not been empirically investigated before. WM load did not affect crosstalk in Experiment 1 of our current study, which is in line with a study by Hommel (1998) that showed that cognitive operations are not limited in capacity. We therefore argue that crosstalk occurs at the time of implementation of rotation parameters and other stimulus features. Later, process execution begins, and feature representations decay unless they are actively maintained in WM. WM maintenance is capacity-limited, and has to compete for WM space with other processes. As a result, implementation is capacity-limited in that only one process can be active at the same time with a possibility to apply this process to more than one stimulus, whereas execution is capacity-limited because it depends on WM maintenance.

In order to find more support for our interpretation of the current results, we examined whether our ideas - as to how only outcomes of procedures and not the procedures itself are stored and take up memory storage in order to avoid decay - can be applied to the task-switching paradigm. In the task-switch paradigm, a task is presented, followed by either a task similar the first – a repetition – or a task different from the first – a switch. Responses to a switch are generally slower than responses to a repetition which is known as the switch cost (Allport, Styles, Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995). Logan (2004) investigated whether WM was necessary for task switching. In his experiment participants memorized three types of tasks that could be applied to the same stimulus set. Subsequently, participants took part in a series of three different tasks. First, they participated in a memory task in which only storage and retrieval of the three types of tasks were measured. Second, Logan conducted a task span which included task switching and task execution in addition to what was required in a memory span. If there was no difference in performance between the two tasks, then task switching and execution were considered not to take up any extra WM capacity. Third, participants performed a control span task in which only one task was presented. Results showed no difference in span between the memory span and task span and no difference in performance between a high or low number of task switches made, suggesting that task switching does not take up WM space. This is in line with the idea that not rule activation but its outcome is stored in WM; the dual-task delay is not caused by the task switch – which itself does not use WM – but by processes that follow.

Liefooghe, Barrouillet, Vandierendonck, and Camos (2008) presented research that followed up on this, and was even closer related to our current experiments. They investigated whether an additional WM load influenced task switching, or that the task switch itself already takes up WM operation. Results showed that it was not the increase in WM task load that affected task-switching costs, but the number of switches made. Liefooghe et al. (2008) attributed the switching costs to serial attention-demanding control processes, in which it is not the task switching itself nor the specific task-set reconfiguration processes that determine the switching costs but the amount of time that attention is engaged during the specific task switch. That is why WM was not affected by the number of switches made and Liefooghe et al. (2008) suggested that WM and task switching are related through simple attention-demanding processes. These studies support our current results that WM seems to be related to certain processes like task switching and that WM is used to maintain codes that are activated by crosstalk but its capacity is not directly used for those processes. This shows that our processing abilities are not fixed, but dependent on the circumstances in which information is presented, in line with functional processing limitation theories. It also shows that our findings can be generalized to other paradigms and that it would be worthwhile to further investigate to what extent stimuli can be activated and influence other stimuli or processes without taxing WM.

Chapter 6

Discussion and Conclusion

Dual-task experiments to investigate working memory and attention

In this thesis, the effect of information-processing overload on working-memory (WM) dependent information processing was examined using dual-task paradigms. Dual-task limitations represent the inability to execute two tasks concurrently: The reaction time (RT) for both tasks is longer and accuracy is lower than when the two tasks would be presented and processed separately (e.g., Bertelson, 1967; Gottsdanker, Broadbent, & Van Sant, 1963). The origin of this delay, and the circumstances that elicit it, still remain unclear. What ís known is that these limitations are largely — if not entirely — determined by attention and WM.

Attention is a multifaceted concept that refers to the way in which limited resources are put to work to process a subset of the available information for the task at hand, be it through spreading the resources (divided and sustained attention), recruiting extra resources (effort, arousal, or alertness), or through investing them selectively for a specific purpose (selective attention). Attention does not only reflect the way processing limitations are handled: controlling attention itself is also a limited-capacity process. It is in the latter sense that the relation between attention and dual-task performance was investigated.

Although several WM models have been proposed, with considerable differences among them (e.g. Baddeley, 2000; Cowan, 1988), they all rely on three main functions: memory storage, cognitive operations on the content of memory, and control (see e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Logie, 1995; D'Esposito, 2007; Oberauer, Demmrich, Mayr, & Kliegl, 2001 for these distinctions). Each of these functions could be responsible for processing limitations. The first function, storage, holds relevant information in WM entering from the outside world or from long-term memory. The second function, operations, processes the information that is stored in memory. The third function controls the operations that occur, for example by biasing one operation over the other so as to select one operation to be performed first. Together, these three functions form an active system in which information is processed.

An example of a WM model was proposed by Baddeley and Hitch (1974; Baddeley, 1986) and was extended by Baddeley in 2000. The model contains the three functions of storage, operations and control and shows three systems that allow for storage and processing of information within a particular domain: the phonological loop, the visual-spatial sketchpad and the episodic buffer. The phonological loop deals with auditory information and is composed of a passive phonological store and an active rehearsal process (Baddeley & Logie, 1999). The visual-spatial sketchpad deals with visual-spatial information and is composed of a storage part called the visual cache, and an active processing system called the inner scribe (Logie, 1995). The episodic buffer (Baddeley, 2000) provides WM with a short-term storage and processing module for information that allows for functions that do not fit the other systems, such as cross-modal integration. The episodic buffer also holds information that is bound with temporal codes in an episodic representation and is subsequently temporarily stored. These subsystems are controlled by the so-called central executive or control system that, for example, manages goal maintenance and updating, and that can focus and switch attention. The differentiation into three parts is theoretically interesting, but not all models accommodate this differentiation to explain WM; instead, some are limited to two of the three components.

Structural and functional processing limitations

The limitations that are present during dual-task processing can be structural or functional in nature, and they each relate in a different way to the three WM functions – storage, operations and control. Structural processing limitations occur when the processing hardware is overloaded by the load of the presented tasks. First, *storage* can be subject to capacity limitations (Kahneman, 1973; Norman & Bobrow, 1975; Navon & Gopher, 1979; Tombu & Jolicœur, 2003). However, which structural underpinnings cause this limited capacity remains unclear. This storage limitation is evident, for example, from the inability to memorize more than a certain number of random words without forgetting some of them. This suggests that information can be processed concurrently until the available WM capacity is exhausted. When more capacity is needed than is available, the encoding of information is either delayed, leading to a later arrival of the information in memory, or the surplus of information is forgotten, leading to a drop in performance.

Second, WM *operations* can be subject to structural processing limitations when relevant information is translated into adequate actions. For example, Pashler (1994) suggested that only one stimulus-response translation process can be performed at a time, analogous to a road lane that passes not more than one car at a time.

Third, structural limitations to executive *control* could lie, for example, in the restriction that in a transition from one task to another it is necessary to reconfigure the task set. Reconfiguring the task set (cf. tracks) causes switch costs which takes up time (Allport, Styles, & Hsieh, 1994), while in a task repetition there is no need for task-set reconfiguration and therefore not for executive control, and hence no extra time costs are incurred (Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995). By analogy, a railroad switch can be set to pass traffic in one direction, and after a switch to pass traffic in another direction, but never more than one direction at a time (Rogers & Monsell, 1995).

Functional-limitation models, on the other hand, attribute the dual-task delay to conflict between simultaneously active task features or processes (Hommel, 1998), to the level of necessary control demands (Luria & Meiran, 2005) or to the strategic settings during a task (Meyer & Kieras, 1997a, 1997b). First, the information that can be *stored* in WM depends on the combination of tasks. For example, storing information of two tasks with completely overlapping responses or features is easier to accomplish than storing information of two tasks with partially overlapping responses or features, arguably because in the latter case the binding of a stimulus feature to an event is preceded by the unbinding of that same stimulus feature from a previous event (Müsseler & Hommel, 1997; Stoet & Hommel, 1999). The Stroop task is a distinct example of how the feature “word-meaning” interferes with the feature “colour-naming” in case the features don’t represent the same colour.

Second, *control* processes can also be subject to impairment because of interference created by incompatible additional control processes. For example, Mayr and Keele (2000) systematically investigated the control process of backward inhibition, when in order to activate a new task set, the previous task set needs to be suppressed. They used an odd-item out task, in which participants had to indicate the deviant stimulus out of four stimuli, depending on dimension. The relevant dimension – color, orientation or movement – was indicated by a verbal cue at the start of each trial. Backward inhibition was measured by presenting the trials in sequences of three: the control condition had a CBA sequence of dimensions, and the inhibition condition had a ĀBA sequence of dimensions. Responses for the third trial (A) in the sequence were slower for the ĀBA trial than the CBA trial. Mayr and Keele argued that this delay was established when activation of the new task set in the B-trial instigated suppression of the task set used in the previous trial. In ĀBA compared to CBA sequences, reactivation of task A in the third task is more difficult in the face of residual suppression of task A. Another example of control processes presents itself when people switch from their first, native language to a second language, this is easier than when they switch from a second language to their first language (Costa & Santesteban, 2004; Meuter & Allport, 1999). A greater suppression of the first language is necessary when the second language is used, while less suppression is necessary for the second language when the first language is required. A switch from second language to first language would take longer because retrieval of the native language takes longer (because it was suppressed more strongly).

Last, limitations also exist for *operations*, in which certain aspects of processing unrelated to load — the so-called content — can influence the dual-task delay. What role these processes play in dual-task slowing, however, has not been investigated before, and can help us understand the underlying mechanisms that cause this delay. One of the aims of this thesis was to clarify exactly this type of dual-task limitations. The hypothesis tested in this thesis was that in a dual task, compatibility between processes of two tasks would decrease dual-task costs, while incompatibility between processes of two tasks would incur an increase in dual-task costs, similar to the way feature processing works.

In sum, structural models on the one hand focus on a set capacity within which restrictions are caused by exceeding this capacity. Functional models on the other hand are more flexible in the sense that it is not only capacity itself, but also how it is used – e.g., the strategy or combination of tasks – that determines its limitations.

Summary of the results

In this thesis the functional role of WM in dual-task processing was investigated, to extend our knowledge on dual-task limitations and why they occur. Dual tasks overload WM and are therefore suited to investigate the origins of capacity limitations. Regarding dual-task limitations, previous research has focused on the structural impairment of dual-task processing, such as a restriction to the number of items stored in WM (e.g., Tombu & Jolicœur, 2003). In the experiments presented in this thesis we aimed to clarify to what extent functional processing limitations affect dual-task processing. More specifically, the aim was to investigate whether process compatibility could facilitate the response to the first of two stimuli in a dual task. This compatibility was varied independent of response category to separate any effect of a category match from the effect of a process compatibility (Chapter 2). Additionally, it was investigated to what extent dual-task limitations observed in different paradigms could be attributed to similar mechanisms. In order to study this, individual WM operation span and IQ were measured and correlated with individual dual-task performance (Chapter 3). Next, the role of attention in dual-task processing was investigated and whether capacity-limited processes and attention might share capacity-limited resources. In order to do so, event-related potentials (ERPs) were used to measure deployment of visual-spatial attention and encoding into visual short-term memory (Chapter 4). The last aim was to investigate whether the effect of response facilitation in case of compatible processes in a dual task was affected by an additional WM load and to determine more specifically the location of dual-task delay (Chapter 5). A summary of the results and their implications is presented below.

Operation compatibility and dual-task costs

The aim in chapter 2 was to examine whether the ability to perform two stimuli concurrently was dependent on task difficulty only – as suggested in structural limitation models (e.g., Pashler, 1994; Tombu & Jolicœur, 2002; 2003) –, or that other factors like compatibility between tasks would also play a role – as suggested in functional limitation models (e.g., Hommel, 1998; Logan & Gordon, 2001; Meyer & Kieras, 1997a; 1997b). We investigated the influence of process compatibility on response speed by presenting two stimuli quasi-simultaneously in a dual task. For both stimuli, a rotated character was presented that required mirror / normal discrimination in a classic mental rotation task (Shepard & Metzler, 1971). Previous research (Corballis, 1986) showed that a stimulus is rotated to upright position before a mirror / normal distinction can be made. Consequently, a stimulus presented in a greater angle from upright will show a slower response (Corballis, 1986; Cooper, 1976). When both tasks required a mirror response or when both tasks required a normal response this was called a category response match. Similarly, rotations were considered compatible when both stimuli needed a clockwise rotation to upright position or both stimuli required a counter-clockwise rotation to upright. We measured the effect of stimulus 2 (S2) processes on reaction time for stimulus 1 (S1), because this shows any facilitation due to simultaneous activation of mental rotation for the two stimuli, whereas an effect of S1 processes on the reaction time to S2 also reflects repetition.

The main result showed a facilitation of the response to S1 when the category responses matched but only when rotations were compatible. This outcome suggests that how fast a task can be processed is not only dependent on the difficulty of the task, but also on the combination of processes. Rotating a stimulus e.g., 60º clockwise or 60º counter-clockwise taxes WM exactly the same; the difference lies in the combination of tasks. This result is an argument against structural models in which dual-task delays are explained in WM-load differences only. The result supports functional processing limitation models in which combination of operations or features, or a strategy are an essential element in explaining dual-task processing.

The second experiment built on the first, and saw S2 moving in a circular path around S1. While S1 was still presented at a particular angle, S2 was presented in upright position. Rotation compatibility was defined as the compatibility between the angle to upright for S1 and the direction of the circular movement for S2.

The main result showed that even though S2 movement was not taxing WM - since not necessary for response - a compatibility between rotations still facilitated the response to S1 in case of a category match. This suggests functional limitations induced by conflict at the level of representing task properties between the direction of mental rotation (Task 1) and the direction of the physical rotation (Task 2).

Similarities between refractory period and attentional blink

The aim in chapter 3 was to investigate whether the delays found in different dual tasks would share a common functional basis (Jolicœur, 1999; Jolicœur &

Dell'Acqua, 1999) or whether their basis would be different (Arnell, Helion, Hurdelbrink, & Pasieka, 2004; Duncan & Arnell, 2002; Wong, 2002). This would ultimately lead to a better understanding of the underlying mechanisms involved in dual-task processing. Thereto, we compared the measures of delay in the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992) and the psychological refractory period (PRP; Telford, 1931; Welford, 1952) and investigated whether they share limitations with respect to a similar mechanism and similar constructs. In the AB, two targets are presented in a string of distractors and require an unspeeded response at the end of the trial. Performance of target 1 and 2 is generally quite high, except for target 2 with intermediate time intervals (100-500 ms post target 1) which shows a marked drop in target-2 performance. This is called the blink (Raymond et al., 1992) and it is the measure of dual-task delay we used for the AB. In the PRP, two targets are presented shortly after each other that need immediate, speeded response. Reaction time for S1 is generally independent of the time interval between S1 and S2 onset. For S2, however, there is an increase in reaction time to S2 as a function of decreasing interval duration between the S1 and S2. This is called the PRP effect (Pashler, 1994; Welford, 1952) and it is the measure of dual-task delay we used for the PRP.

Additionally, we conducted two tasks to measure the constructs underlying WM operation span - which represents mainly the executive control component of WM (Arnell, Stokes, MacClean, & Gicante, in press) - and fluid intelligence (IQ). WM operation span was measured by the OSPAN task (Colzato, Spapé, Pannebakker, & Hommel, 2007; Engle, Kane, Tuholski, 1999; Turner & Engle, 1989) and IQ was measured by the Raven's Standard Progressive Matrices test (Raven, Court, & Raven, 1988). Since WM and IQ are highly correlated but not identical (Conway, Kane, & Engle, 2003; Süβ, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), it is important to control for IQ when a WM construct is correlated with another component. All the components were entered into correlation analysis to investigate the size of the correlation as an indicator of the communality between the two dual tasks.

Results showed that a high blink in the AB correlated with a large PRP effect: people who performed well on the AB also showed proficient performance on the PRP. Additionally, the effects of both paradigms correlated with OSPAN. These two findings both point to a functional relation between AB and PRP. When these correlations between AB magnitude - OSPAN and PRP effect - OSPAN were controlled for IQ, the results showed a small reduction in the respective correlations. The former correlation was still significant; the latter correlation however, was reduced to non-significance, because its initial correlation was somewhat weaker. This suggests that in the AB, WM operation span is more engaged than in the PRP. This could be due to the higher number of stimuli in the AB and the need for participants to filter the targets from distractors. In sum, on the one hand there is evidence for a common functional basis for the dual-task delay in AB and PRP. On the other hand, results showed that OSPAN correlates differently with PRP than with AB and there is still an amount of unexplained variance.

The effect of mental rotation on deployment of visual-spatial attention

In chapter 4, we further investigated dual-task processing and its limitations, this time with the use of electrophysiological measurements. While previous research established response selection as the main culprit for dual-task delay (e.g., Pashler, 1994), we examined whether two processes other than response selection would delay each other. In order to do so, we presented a mental rotation task and a visual-spatial attention task in a PRP set-up to investigate whether shifting visual-spatial attentional processes and subsequent storage of stimuli into visual short-term memory is possible during mental rotation, or whether this is delayed. Earlier studies established mental rotation as capacity limited and preceding response selection (Band & Miller, 1997; Ruthruff, Lachman & Miller, 1995; Van Selst & Jolicœur, 1994). Whether visual-spatial attention causes capacity limitations is less clear, with some evidence showing no limitation (Johnston, McCann, & Remington, 1995; Pashler, 1991) and other evidence showing the opposite: Brisson & Jolicœur (2007a; 2007b) showed that response selection postpones attentional processes of a second task.

Results in our current experiment showed that mental-rotation caused a delay for visual-spatial attention in the second task. The deployment of attention and the arrival of information into visual short-term memory were measured with two components of the ERP. First, the N2pc was used as a measure of deployment of attention. Second, the sustained posterior contralateral negativity (SPCN) was used as a measure of encoding information into visual short-term memory. These results suggest that processes preceding response selection (i.e. mental-rotation and visual-spatial attention) could not be processed concurrently and response selection is not necessary for the dual-task delay to occur. Furthermore, the results indicated that response selection, mental rotation and visual-spatial attention are likely to share a common resource like executive control.

Cognitive operations and working memory

The aim in chapter 5 was twofold. First, we wanted to further explore the contribution of functional processing limitations to general dual-task limitations. Second, we wanted to make a further specification as to exactly which processes are capacity limited. Thereto, we conducted two experiments that were both a continuation of chapter 2. The same dual task as in experiment 1 of chapter 2 was presented with a mental rotation for both tasks. Again, we measured rotation compatibility and category response match. This time, we added an extra WM task aimed to take up considerable WM space during the course of the trial. We were interested to see the effect of this on compatibility independent of category response match.

Results showed that even though a considerable part of WM was taken up by this background WM task, there was still a facilitation of the response to S1 when the category responses matched but only when rotations were compatible. While WM was significantly taxed, still one process could activate two stimuli and open the way for category match to facilitate the response. Specifically, this result suggests that crosstalk is not dependent on WM storage. Instead, it is probably the outcome of the processes that are stored in WM to avoid decay. In general, these results stress the necessity to incorporate a component that explains functional-processing limitations in any model that is used to describe dual-task limitations.

In the second experiment, we focused on the finding that category match facilitates the response to S1, but only in case of a rotation compatibility. Which process constitutes the main limitation of this operation of mental rotation? Is it the implementation of the rotation, or the execution of the rotation? In order to investigate this we separated the onset of these two processes. We presented a cue at the start of each trial that validly predicted the stimulus angle in task 2 75% of the time. This cue gave participants the opportunity to implement the rotation before each trial, while S2 presentation triggered the execution of the mental rotation.

Results showed that implementing different parameters of the same operation is possible, but the execution of the operation is serial. This outcome suggests that implementation is not capacity limited, and does not take up WM space. The capacity limitation could be caused by the active use of WM space by execution processes.

The current results fitted in relevant dual-task models

The results (specifically Chapters 2 and 5) show that, in order to accommodate crucial aspects of the findings summarized in the preceding section, any model of dual-task limitations, especially WM models, should include an explanation for functional processing limitations. Dual-task limitations that are caused by the way processes are combined cannot be explained sufficiently by structural-limitation models. Three models provide or imply a functional explanation of processing limitations: 1) the Executive-Process/Interactive Control model (EPIC; Meyer & Keiras, 1997a, 1997b), 2) the Executive Control Theory of Visual Attention (ECTVA; Logan & Gordon, 2001) and 3) the Theory of Event Coding (TEC; Hommel, Müsseler, Aschersleben, & Prinz, 2001).

First, the EPIC model describes dual-task limitations as strategic, and suggests that under optimal circumstances, dual-task limitations will be decreased to none (Schumacher et al., 2001). A delay occurs when the strategy of the participants results in a more serial processing mode.

Second, the ECTVA model (Logan & Gordon, 2001) is a hierarchical model in which the executive control coordinates which parameters are manipulated at any one time. It uses an extension of the parameters put forward in the Theory of Visual Attention (TVA; Bundesen, 1990). The TVA is run twice; once for each of the two tasks in a dual task. Set-switching costs, concurrence costs and crosstalk all affect the dual-task delay. Set-switching costs depend on how many parameters need adjusting and how much adjusting they need. Costs involved in keeping two tasks active are called concurrence costs. However, there is always one task that is prioritized, and only when the set of one task can be applied to the stimulus from another task (i.e., when the stimulus or response sets of the two tasks overlap), crosstalk occurs.

Third, the TEC is aimed to provide a functional framework for perception and action that stores them together in one module called the unified coding medium (Hommel et al., 2001). It includes relevant and irrelevant features of stimuli, operations and responses (actions). In the unified encoding medium different feature codes are bound together into an event file. For example, the feature codes ‘edible’, ‘red’, ‘grows-on-trees’ and ‘round’ can be combined into an event file named ‘apple’. Because the TEC uses one module for stimulus features and response features, it allows for relevant and irrelevant features to be activated within the same medium which can cause interaction. This interaction can take place between stimulus features, response features, or between stimulus- and response features. This line of reasoning can explain the results in experiment 2 of chapter 2 of this thesis, in which a nondemanding, irrelevant movement of the S2 in a circular path around S1 facilitated the response to S1 when this movement was compatible with the rotation direction of S1. While this outcome was in line with the predictions of the TEC, the EPIC or ECTVA would only predict an effect when task load (or WM load) was manipulated. Additionally, the TEC differs from multi-modular models like the multi-component WM model by Baddeley and Hitch (1974; Baddeley, 2000). In their model, visual-spatial information, auditory information and episodic information is stored in separate modules that are controlled by a higher order central executive. Multi-component models cannot explain the cross-over effects of different elements in different event files because the information is not stored together, and action processes are not taken into consideration.

Attention and capacity-limitations

Brisson and Jolicœur (2007a; 2007b) showed that visual-spatial attention is delayed by response selection. Additionally, with the results presented in chapter 4 we showed that visual-spatial attention is delayed by mental rotation — a bottleneck process preceding response selection. Thus, response selection is not the only process responsible for the dual-task delay in the PRP paradigm and, moreover, is not necessary for the PRP effect to occur. During mental rotation visual-spatial attention is put (partly) on hold, either because visual-spatial attention in itself is capacity limited (like mental rotation), or because visual-spatial attention is regulated by a top-down process.

We showed that when processes like mental rotation are active, visual-spatial attentional selection processes are postponed. This suggests that when WM is activated by mental rotation, visual-spatial attention cannot be active concurrently. This in turn suggests that instead of a unitary process, attention is a set of related but separate selection processes in which visual-spatial attention competes with mental rotation to be selected by central attention that prioritizes the different processes. A model that has incorporated attention in its WM framework is the embedded-process model of WM proposed by Cowan (1988; 1995). The model consists of a three-layered core, containing a long-term memory store, a short-term activated memory store and a focus of attention. Long-term memory has the least restricted capacity and the focus of attention has the most restricted capacity. The limited short-term activated memory store is part of the larger long-term memory store. Within the short-term activated memory store, the focus of attention selects one item at a time, just like a real spotlight singles out items in the dark (see also Oberauer, 2002). The focus of attention is directed top-down by a central executive on the one hand, and bottom-up by stimuli that are new or relevant on the other hand. Consequently, visual-spatial attention is considered a process that regulates the focus of attention bottom-up (by stimulus presentation), and then takes up the limited capacity available and in that way interferes with mental rotation and response selection. Alternatively, visual-spatial attention is regulated by a limited-capacity top-down process which in turn also causes interference.

Future research

The general aim of this thesis was to investigate the functional limitations of dual-task processing, to obtain a better understanding of the reason why they occur and to what extent they are limited, of the relation between different dual tasks, of the attentional processes involved during dual-task processing, and of WM in general.

Although this thesis has done exactly that, this doesn't mean that there are no remaining questions or for that matter new questions to be answered.

Questions that still require an answer are mostly concerned with the circumstances in which dual-task delay occurs. In what way can the organisation of information influence the amount of information that can be stored or processed, and what are the core parameters that underlie or limit these processes? Is there a delaying effect of organization of demanding tasks, related to the exertion of executive control? In what way does the combination of e.g., task sets, stimuli, processes and responses influence the delay in the organization of executive control, without influencing the overall available capacity itself?

The use of tools like EEG (electro-encephalogram), fMRI (functional magetic resonance imaging) or MEG (magneto-encephalogram) opens up an interesting approach, because it allows us to measure differences that cannot be distinguished behaviourally. For example, the ERP component N2pc (e.g., Eimer, 1996; Luck & Hillyard, 1994) can be used as a measure for deployment of attention in a way behavioural measures cannot. Similarly, the P3 (e.g., Donchin, 1981; Donchin & Coles, 1988; Vogel, Luck, & Shapiro, 1998) – also an ERP component – can be used as a measure of activity associated with relevant representations in short-term memory or context updating (Donchin & Coles, 1988). More recently, Shapiro, Schmitz, Martens, Hommel, and Schnitzler (2006) used the size of the P3 as a measure of the amount of resources invested in processing a particular target.

One paradigm in which performance differs between participants and between conditions is the AB paradigm, which depends for example on the individual's WM operation span (e.g., Colzato et al., 2007; see also Chapter 3 of this thesis), or possibly on one's mental state (Olivers & Nieuwenhuis, 2005). In the latter study, half of the participants conducted an AB task, and the other half conducted the same AB task while performing a background task, e.g., responding to a yell presented in a background beat. Results showed increased target 2 performance when the background beat was present. They gave a functional interpretation to the AB results and argued that a more diffused mental state would allow better AB performance.

Shapiro et al. (2006) also investigated whether the bottleneck that causes the blink in the AB paradigm was structural or functional. They used magnetoencephalography to measure target 1 related P3 (M3) and found a correlation between target 1 peak amplitude and the size of the blink. Shapiro et al. (2006) argued that the division of capacity over two tasks in an AB paradigm can predict the performance on the two tasks. This suggests a functional division of resources and further research could be aimed at investigating how this balance of resources between the two targets can be manipulated.

By using a background beat as between-subjects variable in an AB paradigm like Olivers and Nieuwenhuis (2005) and measuring the difference in amount of resources invested in target 1, the hypothesis could be tested whether subjects overinvest resources to the target 1 at blink trials, at the expense of the available resources for target 2, and whether this overinvestment is less likely to occur in a more diffused mental state. We investigated this in a pilot study using the P3 as a measure of investment of resources in target 1 and target 2 and found no distinct results. This could be attributed to the between-subjects set-up of our study, and further research could do a lot to clarify how the division of resources operates.

In closing

To conclude, the experiments described in this thesis contribute to the vast amount of dual-task research already available, strengthening the importance of a functional explanation for dual-task limitations. First, it showed evidence for a unified coding medium (as put forward in the TEC) in which features, operations and responses are available and can influence each other. Additionally, it was shown that the response to the first of two stimuli is facilitated in case the processes are compatible (Chapter 2). Furthermore, it showed that the PRP and the AB share limitations with respect to a common resource that originates in WM operation span and that the use of individual differences can aid in examining the relation between the PRP and the AB (Chapter 3). Additionally, it showed that it is plausible that visual-spatial attention, mental rotation and response selection share limitations with respect to a common resource (Chapter 4). Finally, research in this thesis showed that processes that can facilitate a response can be simultaneously implemented but not simultaneously executed (Chapter 5). All in all, dual-task limitations can ultimately show us the boundaries of WM.

On a more general note, some advice for anyone who keeps running out of time (and who doesn’t these days): Take at heart the words spoken by Lord Chesterfield (1694-1773; published in 1774) who said: “There is time enough for everything in the course of the day, if you do but one thing at once, but there is not time enough in the year, if you will do two things at a time.” and limit yourself to doing one thing at a time!

Chapter 7

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Appendix A

Summary in Dutch
(Samenvatting)

In onze hersenen vinden verschillende processen plaats, zoals bijvoorbeeld het reguleren van autonome activiteiten als ademen, coördinatie van bewegingen, maar ook perceptie (zien, horen) en zogenaamde hogere hersenprocessen als taal, plannen, en geheugen. Het werkgeheugen is onderdeel van het geheugen en heeft als functie het onderhouden en het actief verwerken van informatie. Het wordt geactiveerd als informatie relevant is voor een bepaalde situatie of taak. Het wordt ook gebruikt bij processen als het ophalen, bewerken en het combineren van informatie. Werkgeheugen heeft een beperkte capaciteit, wat tot uiting komt bij overbelasting, bijvoorbeeld bij het onthouden van een lange boodschappenlijst, of bij het doen van meerdere taken tegelijkertijd (multitasken) waarbij we snel dingen vergeten. Bij de bestudering van het werkgeheugen maken we gebruik van een systematische overbelasting van het werkgeheugen om zo de invloed op prestatie te onderzoeken. In het onderzoek dat ten grondslag ligt aan dit proefschrift wordt het werkgeheugen overbelast door twee taken tegelijkertijd uit te voeren.

Het doen van twee dingen tegelijkertijd ofwel het uitvoeren van een dubbeltaak is iets wat we iedere dag doen, bijvoorbeeld wanneer we autorijden en tegelijkertijd ‘handsfree’ bellen. Dit is relatief makkelijk als het bellen gebeurt op een lege snelweg, maar een stuk moeilijker op een drukke rotonde. Een omgeving waar weinig gebeurt, zoals thuis op de bank, is de makkelijkste manier om iemand te bellen. Twee dingen tegelijkertijd doen kost altijd meer tijd dan één ding tegelijk doen (bv. Bertelson, 1967; Gottsdanker, Broadbent, & Van Sant, 1963) omdat het werkgeheugen beperkt is. De vertraging die optreedt wanneer je twee taken tegelijkertijd uitvoert hangt niet alleen af van de moeilijkheid van de taak, maar ook van de combinatie van verschillende taken (bv. Hommel, 1998; Logan & Schulkind, 2000). De oorzaak van deze vertraging, en omstandigheden waaronder de vertraging ontstaat, is nog onduidelijk. Wel is bekend dat deze beperkingen vooral afhangen van aandacht en werkgeheugen.

Veelgebruikte dubbeltaken zijn de psychological refractory period (PRP) taak en de attentional blink (AB) taak. In de PRP taak worden twee stimuli kort na elkaar gepresenteerd; het tijdsinterval tussen beide stimuli wordt gevariëerd. De respons wordt direct gegeven en de reactiesnelheid is belangrijk. De reactiesnelheid op de eerste stimulus is over het algemeen onafhankelijk van het tijdsinterval tussen stimulus 1 en stimulus 2. De reactietijd op stimulus 2 wordt echter langer als het tijdsinterval kleiner wordt. Dit effect wordt het PRP effect genoemd (Pashler, 1994; Welford, 1952) en wordt gebruikt als een maat voor dubbeltaakvertraging. In de AB taak worden twee stimuli gepresenteerd in een reeks van één voor één gepresenteerde distractoren: het aantal distractoren tussen beide stimuli wordt gevarieerd. De responses worden gegeven aan het einde van een trial en alleen de proportie correct wordt gemeten;

reactietijd is niet belangrijk op deze taak. De prestatie op beide stimuli is over het algemeen vrij goed, behalve als de tweede stimulus tussen de 100 ms en 500 ms na stimulus 1 wordt gepresenteerd met minimaal één distractor tussen beide stimuli: dan is prestatie slechter. Deze verminderde prestatie wordt de blink – ofwel knipper – genoemd (Raymond, Shapiro, & Arnell, 1992) omdat het net is alsof de aandacht even weg is, net zoals wanneer het zicht even weg is als je met je ogen knippert.

Beperkingen die optreden tijdens het uitvoeren van twee paralelle taken kunnen veroorzaakt worden door beperkte capaciteit van het werkgeheugen of door beperkingen in de combinaties van stimuluskenmerken of –processen. Structurele verwerkingsbeperkingen worden veroorzaakt door de beperkte capaciteit, en het onderzoek daarnaar richt zich op de verhouding tussen taakmoeilijkheid (belasting) en de verwerkingscapaciteit. Wanneer meer capaciteit nodig is dan op dat moment beschikbaar, dan wordt bijvoorbeeld het encoderen van informatie vertraagd, wat leidt tot een verlaagde taakprestatie. Theorieën van functionele verwerkingsbeperkingen schrijven de beperking toe aan het conflict dat ontstaat tussen gelijktijdig geactiveerde kenmerken of processen (Hommel, 1998), aan de controle die nodig is (Luria & Meiran, 2005) of aan de strategische opzet tijdens een taak (Meyer & Kieras, 1997a, 1997b). Het is bijvoorbeeld makkelijker om twee taken met helemaal overlappende responsen en kenmerken uit te voeren dan twee taken met gedeeltelijk overlappende responsen en kenmerken. De oorzaak hiervan kan erin liggen dat stimuluskenmerken pas in een nieuwe combinatie verbonden kunnen worden nadat eerder gevormde combinaties van die stimuli zijn ontbonden (Müsseler & Hommel, 1997; Stoet & Hommel, 1999). Eén van de doelen van dit proefschrift was om de bijdrage van deze functionele beperkingen op het verwerken van dubbeltaken te bestuderen.

Doel van dit proefschrift

Eerder onderzoek heeft uitgewezen dat dubbeltaken gebruikt kunnen worden om beperkingen in het werkgeheugen te bestuderen. Verder heeft onderzoek laten zien dat de vertraging die optreedt wanneer twee taken tegelijkertijd worden uitgevoerd, wordt veroorzaakt door structurele verwerkingsbeperkingen. Naast structurele verwerkingsbeperkingen zijn ook enkele functionele verwerkingsbeperkingen vastgesteld. Dit betekent echter niet dat we precies weten waar deze beperkingen vandaan komen. Het algemene doel van dit proefschrift was om de rol van functionele beperkingen in dubbeltaken te onderzoeken, om een beter idee te krijgen van de oorzaak van deze beperkingen en in hoeverre deze gelden. Meer specifiek omschreven is in een dubbeltaak de invloed van compatibiliteit tussen processen op taakprestatie gemeten. Deze compatibiliteit werd onafhankelijk van responscategorie gevarieerd om interferentie van een match in categorieën te onderscheiden van het effect van procescompatibiliteit (Hoofdstuk 2). Daarnaast is onderzocht in welke mate de beperkingen van verschillende dubbeltaken konden worden toegeschreven aan vergelijkbare mechanismen. Hierbij zijn de individuele werkgeheugen operation span en IQ gemeten en hun samenhang met de individuele dubbeltaakprestatie (Hoofdstuk 3). Vervolgens is de rol van visueel-spatiële aandacht in de verwerking van dubbeltaken onderzocht. De vraag hierbij was of visueel-spatiële aandacht en andere belastende processen onderhevig zijn aan dezelfde capaciteitsbeperking. Daartoe zijn event-related potentials gemeten. Een event-related potential is een electrische potentiaal geassocieerd met een specifieke gebeurtenis (Luck, 2003). De event-related potential wordt toegepast om het gebruik van visueel-spatiële aandacht te meten en de encodering van deze visueel-spatiële informatie in het visueel korte-termijn geheugen (Hoofdstuk 4). Een laatste doel was de invloed van een extra werkgeheugenbelasting op de verwerking van compatibele processen te meten en om de specifieke locatie van de dubbeltaakvertraging beter te bepalen (hoofdstuk 5). Een samenvatting van de resultaten en de implicaties daarvan wordt hieronder beschreven.

Samenvatting van de resultaten

Compatibiliteit van processen en dubbeltaakvertraging

Het doel van hoofdstuk 2 was om te onderzoeken of het vermogen om twee stimuli tegelijkertijd te verwerken alleen afhankelijk is van de moeilijkheid van de taak – zoals gesuggereerd in structurele modellen over dubbeltaakbeperkingen (bv. Pashler, 1994; Tombu & Jolicœur, 2002; 2003) – of dat andere factoren als compatibiliteit tussen taken ook een rol speelt – zoals gesuggereerd in functionele modellen (bv. Hommel, 1998; Logan & Gordon, 2001; Meyer & Kieras, 1997a; 1997b). De invloed van compatibiliteit van processen op de snelheid van de respons werd gemeten in de PRP.

In de dubbeltaak in hoofdstuk 2 werd in beide taken een letter of een cijfer aangeboden. Dit alfanumerieke karakter kon normaal of in spiegelbeeld weergegeven zijn, en kon met de klok mee of tegen de klok in gedraaid staan. De taak voor de proefpersoon was om te beoordelen of de tekens normaal of in spiegelbeeld stonden. Het lukt de proefpersoon alleen om dit te beoordelen door eerst het teken mentaal naar de normale stand te roteren. Als deze tekens allebei normaal of allebei in spiegelbeeld afgebeeld zijn dan matchen zowel de responscategorieën (ze zijn allebei normaal of allebei in spiegelbeeld gepresenteerd) als de processen (beide stimuli draaien via de kortste weg tegen de klok in naar rechtopstaand). Er zijn ook andere combinaties mogelijk: als het ene teken normaal en het andere teken in spiegelbeeld is gepresenteerd, dan is er een mismatch tussen de responscategorieën. Wanneer het ene teken klokwaarts de snelste weg naar rechtop volgt, en het andere teken tegen de klok in, dan zijn de processen niet compatibel.

Het voornaamste resultaat van dit experiment is facilitatie van de respons op stimulus 1 als de responscategorieën matchen, maar alleen als de bijbehorende processen compatibel zijn. Deze facilitatie van de respons op stimulus 1 bij matchende responscategorieën suggereert dat de reactiesnelheid op een taak niet alleen afhangt van de moeilijkheidsgraad, maar ook van de combinatie van taakprocessen. De compatibiliteit van processen heeft geen gevolgen voor de werkgeheugenbelasting en de moeilijkheid van de taak verschilt dus niet. Dit resultaat gaat in tegen de structurele dubbeltaakmodellen waarin dubbeltaakvertraging alleen wordt verklaard door de taakmoeilijkheid. Het resultaat is een argument vóór functionele dubbeltaakmodellen waarin niet alleen de taakmoeilijkheid maar ook de combinatie van taakkenmerken of – processen van invloed is op taakprestatie.

In het tweede experiment werd de compatibiliteit tussen een proces (mentale rotatietaak) van stimulus 1 en een irrelevante, fysieke beweging van stimulus 2 bekeken. De beweging van stimulus 2 rondom stimulus 1 is niet belastend voor het werkgeheugen aangezien de beweging van stimulus 2 irrelevant voor de respons is. Het experiment laat weer facilitatie zien van de respons op stimulus 1 als de responscategorieën matchen, maar alleen als de bijbehorende processen compatibel zijn. Dit suggereert een conflict tussen de richting die het teken in taak 1 via de kortste weg naar rechtop draait en de richting van de fysieke rotatie in taak 2. Omdat de combinatie van een proces (mentale rotatie) met een fysieke beweging geen verschil introduceert in de taakmoeilijkheid, is dit een argument voor functionele beperkingsmodellen.

Overeenkomsten tussen de PRP en de AB

Het doel in hoofdstuk 3 was om te onderzoeken of de vertraging die optreedt in verschillende dubbeltaken een volledige gezamenlijke functionele basis heeft (Jolicœur, 1999; Jolicœur & Dell'Acqua, 1999) of slechts gedeeltelijk (Arnell et al., 2004; Duncan & Arnell, 2002; Wong, 2002). Dit onderzoek kan bijdragen aan een beter begrip van de onderliggende mechanismen van dubbeltaakprocessen. We hebben de samenhang tussen de AB (Raymond et al., 1992) en de PRP (Telford, 1931; Welford, 1952) onderzocht. De vraag hierbij was of de vermindering in prestatie bij de AB en de vertraging in reactiesnelheid bij de PRP een gezamelijke of een verschillende basis hebben. Naast deze twee taken zijn ook IQ en werkgeheugen operation span (een maat voor de grootte van het actieve gedeelte van het werkgeheugen) gemeten. De samenhang tussen IQ en werkgeheugen operation span met zowel AB en PRP helpt bij het beantwoorden van bovenstaande vraag.

De resultaten laten zien dat een hoge blink in de AB samenhangt met een groot PRP effect. Daarnaast hing een goede prestatie op beide dubbeltaakeffecten (bij AB iets meer) samen met een hoge score op werkgeheugen operation span. Deze twee bevindingen wijzen op een functionele relatie tussen AB en PRP. Correctie voor IQ zorgde voor een kleine reductie van de samenhang zowel tussen de AB en werkgeheugen operation span als tussen de PRP en werkgeheugen operation span. De eerste correlatie bleef bestaan maar de tweede correlatie verdween doordat deze tweede correlatie vóór de correctie al iets zwakker was. Dit suggereert dat werkgeheugen operation span meer gebruikt wordt tijdens de AB dan tijdens de PRP. Een oorzaak hiervan zou het hogere aantal distractoren in de AB kunnen zijn en de noodzaak voor de proefpersonen om deze weg te filteren. Samenvattend is er aan de ene kant bewijs voor een gezamenlijke functionele basis voor de vertraging die optreedt tijdens het uitvoeren van een dubbeltaak. Aan de andere kant laten de resultaten zien dat de werkgeheugen operation span sterker correleert met de AB dan de PRP en dat er nog steeds een deel onverklaarde variantie is.

Het effect van twee niet-responsselectie processen op dubbeltaakvertraging

In hoofdstuk 4 zijn dubbeltaakprocessen en –beperkingen verder onderzocht, deze keer met behulp van electrofysiologische metingen. In eerder onderzoek is gesuggereerd dat responsselectie de voornaamste oorzaak van de dubbeltaakvertraging is (e.g., Pashler, 1994; Tombu & Jolicœur, 2003). Resultaten in dit hoofdstuk wijzen er op dat dubbeltaakvertraging ook kan ontstaan bij het uitvoeren van twee processen waarbij géén responsselectie gebruikt wordt. In dit geval werd een vertraging van het verplaatsen van visueel-spatiële aandacht en het arriveren van die informatie in het visueel korte-termijn geheugen van taak 2 door een capaciteitsbeperkend proces (mentale rotatie) in taak 1 gemeten door twee componenten van de event-related potential. Allereerst werd de N2pc gebruikt als maat voor het gebruik van spatiële aandacht. Als tweede werd de sustained posterior contralateral negativity (SPCN) gemeten als maat voor het encoderen van informatie in visueel korte-termijn geheugen. Deze resultaten wijzen er op dat de processen mentale rotatie en visueel-spatiële aandacht - die beiden voorafgaan aan responsselectie - niet tegelijkertijd kunnen plaatsvinden en dat responsselectie niet de enige oorzaak is van dubbeltaakbeperkingen. Verder laten de resultaten zien dat responsselectie, mentale rotatie en visueel-spatiële aandacht waarschijnlijk alledrie een beroep doen op cognitieve controle. De organisatie van cognitieve controle heeft een beperkte capaciteit of zorgt ervoor dat de processen achter elkaar plaatsvinden waardoor er dubbeltaakvertaging optreedt. Deze resultaten kunnen worden verklaard met functionele modellen (bv. Logan & Gordon, 2001; Meyer & Kieras, 1997a; 1997b).

Compatibiliteit tussen processen, werkgeheugen en dubbeltaakvertraging

Het doel in hoofdstuk 5 was tweeledig. Allereerst is in experiment 1 de bijdrage van functionele verwerkingsbeperkingen aan dubbeltaakbeperkingen verder onderzocht. Ten tweede is in experiment 2 gespecificeerd welke processen nu precies capaciteitsbeperkend zijn. In experiment 1 werd een extra werkgeheugentaak toegevoegd aan het eerste experiment in hoofdstuk 2 die er op gericht was een substantieel gedeelte van de werkgeheugenruimte in beslag te nemen tijdens de uitvoering van de PRP taak. Het doel was te onderzoeken of deze extra werkgeheugentaak invloed had op de snelheid van de respons op stimulus 1 als de responscategorieën matchten en de processen van taak 1 en taak 2 compatibel waren.

De resultaten laten zien dat alhoewel een aanzienlijk gedeelte van het werkgeheugen inderdaad werd ingenomen door de extra taak, er nog steeds facilitatie was van de respons op stimulus 1 in het geval van een match tussen de responscategorieën en de processen van taak 1 en taak 2 compatibel waren. Dit resultaat suggereert dat de invloed van stimulus 2 processen op de respons op stimulus 1 niet afhankelijk is van werkgeheugenopslag. Het zijn waarschijnlijk niet de processen zelf die worden opgeslagen in het werkgeheugen maar juist de uitkomsten van deze processen zodat deze actief blijven en niet vergeten worden. In het algemeen onderstrepen deze resultaten de noodzaak om een functionele component in dubbeltaak beperkingsmodellen toe te voegen.

In het tweede experiment is de aandacht gericht op de vondst dat een match tussen de responscategorieën de respons op stimulus 1 faciliteert maar alleen bij compatibele processen. De beperking van het tegelijkertijd uitvoeren van twee processen kan liggen in de implementatie of in de uitvoering van een taak. De resultaten laten zien dat het implementeren van verschillende parameters van hetzelfde proces mogelijk is, maar dat de uitvoering daarvan serieel plaatsvindt. Deze uitkomst suggereert dat implementatie geen capaciteitsbeperkingen heeft en geen werkgeheugenruimte inneemt. De capaciteitsbeperking zou veroorzaakt kunnen worden door het actieve gebruik van werkgeheugenruimte door de uitvoeringsprocessen.

Afsluiting

De resultaten van de experimenten over dubbeltaken, werkgeheugen en visueel-spatiële aandacht beschreven in dit proefschrift laten het belang zien van een uitleg van dubbeltaakprestaties aan de hand van functionele beperkingen. Allereerst werd aangetoond dat compatibiliteit tussen processen de responssnelheid faciliteert (Hoofdstuk 2). Daarnaast toonde onderzoek in dit proefschrift aan dat de dubbeltaken

PRP en AB capaciteitsbeperkingen een gemeenschappelijke oorsprong hebben. Deze oorsprong wordt gedeeld met werkgeheugen operation span en niet met IQ (Hoofdstuk 3). Tegelijkertijd werd in dit proefschrift aannemelijk gemaakt dat visueel-spatiële aandacht, mentale rotatie en responsselectie waarschijnlijk alledrie een beroep doen op cognitieve controle (Hoofdstuk 4). Als laatste toonde onderzoek in dit proefschrift aan dat de facilitatie tussen processen geen beroep doet op werkgeheugenopslag, en dat deze facilitatieprocessen wel tegelijkertijd geimplementeerd maar niet tegelijkertijd uitgevoerd kunnen worden (Hoofdstuk 5). Concluderend kunnen beperkingen in het uitvoeren van dubbeltaken ons de grenzen van het werkgeheugen laten zien.

Op een luchtigere toon, als laatste wat advies voor iedereen die te weinig tijd heeft (en wie heeft dat tegenwoordig niet): neem de wijze woorden van Lord Chesterfield (1694-1773) ter harte die zei: *“Er is genoeg tijd in de dag als je alles achter elkaar doet maar er is niet genoeg tijd in een jaar als je twee dingen tegelijk doet”* en beperk jezelf tot het doen van één ding tegelijk!

Appendix B

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Appendix C

Curriculum Vitae

Merel Mathilde Pannebakker werd geboren op 19 februari 1977 in Schiedam. Vanaf 1989 volgde zij de VWO opleiding aan het Bernardinus College te Heerlen. Van 1996 tot 2004 studeerde Merel Geneeskunde en Psychologie aan de Universiteit Leiden. In 2004 studeerde zij af in de Cognitieve Psychologie, met een afstudeerscriptie over werkgeheugen en priming. Van 2004 tot 2009 werkte zij aan haar promotieonderzoek naar de beperkingen van dubbeltaakverwerking met behulp van gedrags-, en EEG maten aan de Leidse Universiteit. De resultaten hiervan zijn in dit proefschrift beschreven.

Op dit moment is Merel werkzaam aan de Universiteit van Cambridge bij de Cambridge Intellectual and Developmental Disabilities Research Group aan een project over de gezondheid en het welzijn van volwassenen met een neurologische ontwikkelingsstoornis geassocieerd met een verstandelijke beperking.