Limitations in dual-task performance

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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.

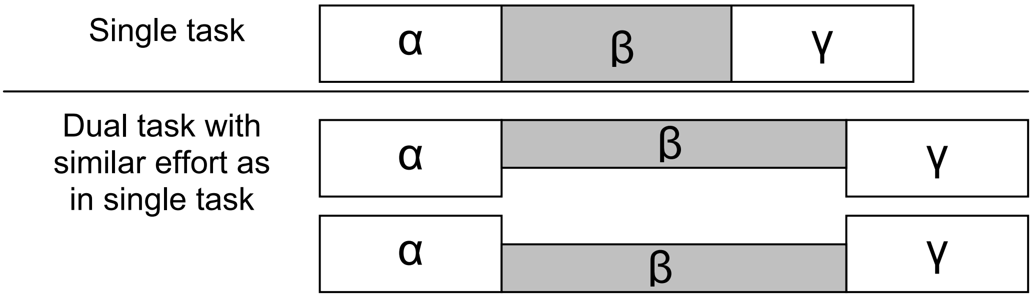

Figure 1.1. Conducting the two tasks from a dual task takes longer than conducting a single task. This is caused by a capacity-limited process (block β; in grey), while processes before and after this capacity-limited process (blocks α & γ; in white) are not affected. The lower panel illustrates a model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

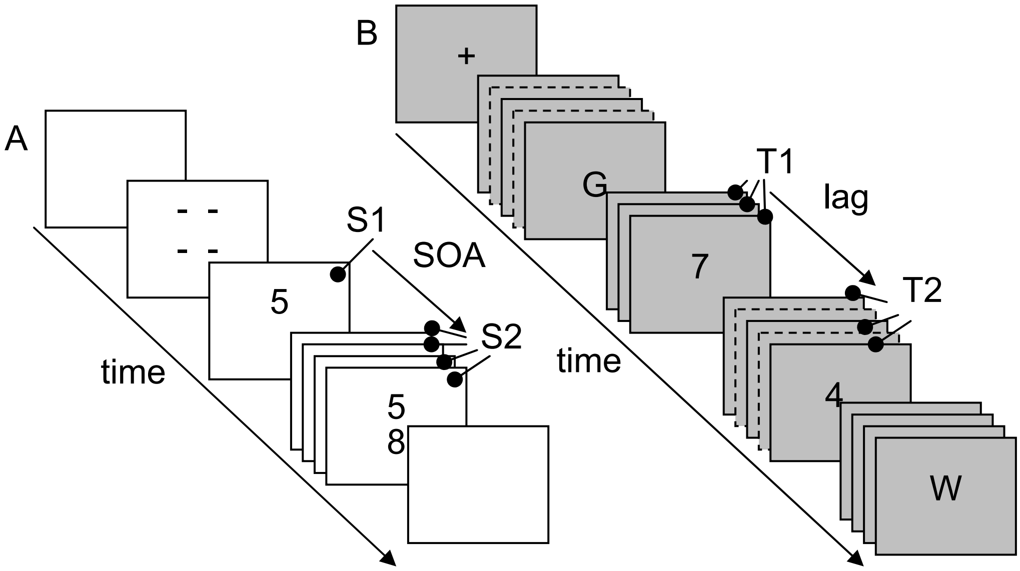

Figure 1.2. (A) An example of a PRP trial. After the fixation that indicates the boundaries in which the stimuli are presented, S1 is presented and after a delay – the SOA – S2 is also presented on the screen. Responses for both stimuli are speeded. (B) An example of an AB trial. After a fixation that 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.

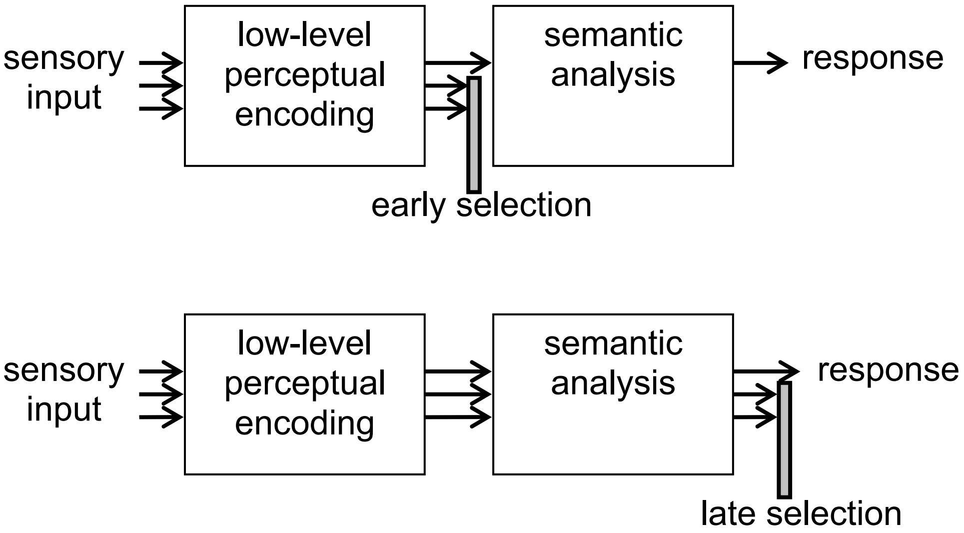

Figure 1.4. Schematic presentation of the early vs. late selection models of attention

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).

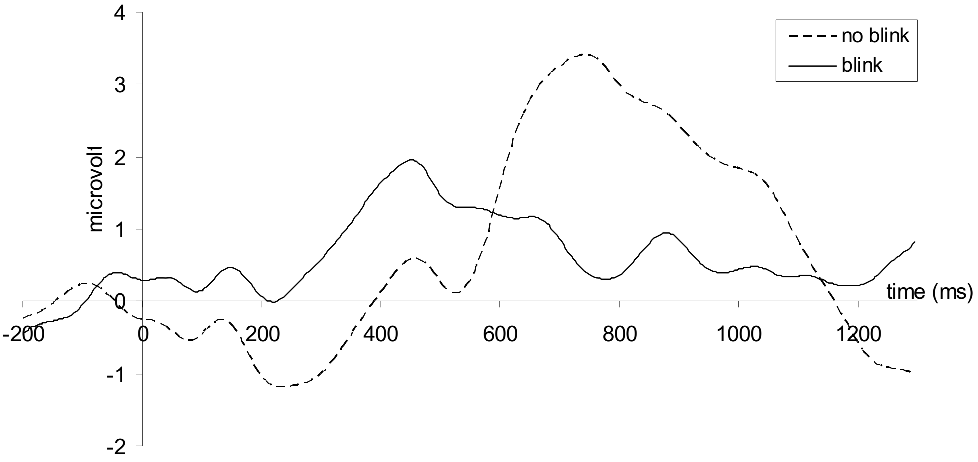

Figure 1.5. An example of an event related potential waveform measured over the medial posterior side of the head. Target 2 is presented at 360 ms and the P3 starts to rise 400 ms later at 750 ms with a peak at 900ms. The dotted line represents the correct (no-blink) trials and is high in amplitude.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

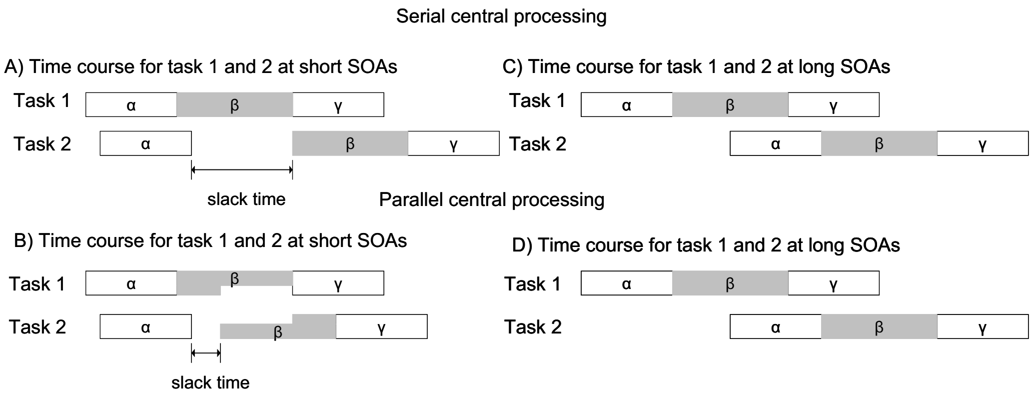

Figure 1.6. An overview of the time course of the serial processing model and the parallel processing model for short and long SOA

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