Limitations in dual-task performance

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Chapter 5

Capacity Limitations of Cognitive Operations

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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).

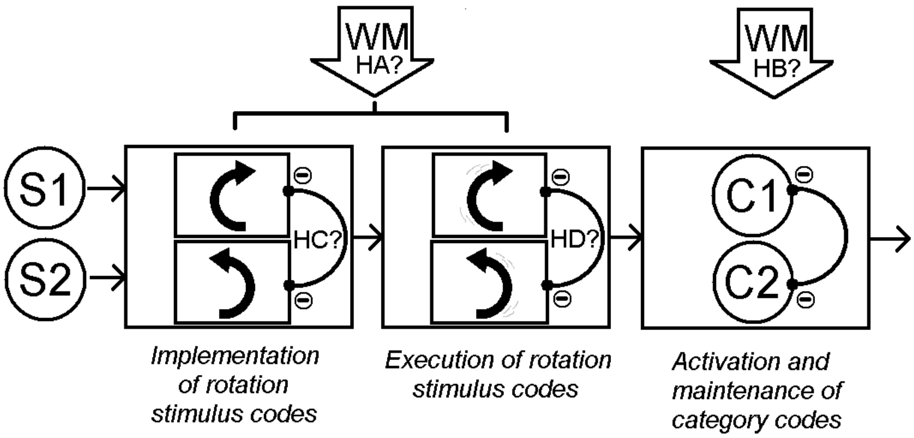

Figure 5.1. Schematic representation of the different subprocesses (i.e. rotation, category code activation) and their relation with working memory (WM). Two stimuli are entered into the model and subsequently need clockwise or counterclockwise rotation (represented by the rotating arrows inside the 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.

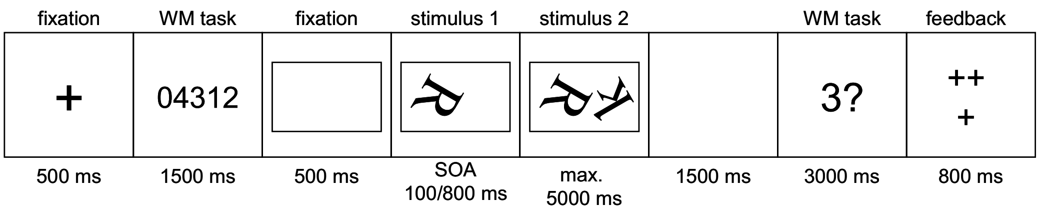

Figure 5.2. Sequence of events within one trial in Experiment 1: A PRP paradigm containing two rotated letters in the centre of the screen during which a WM load has to be maintained active

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.

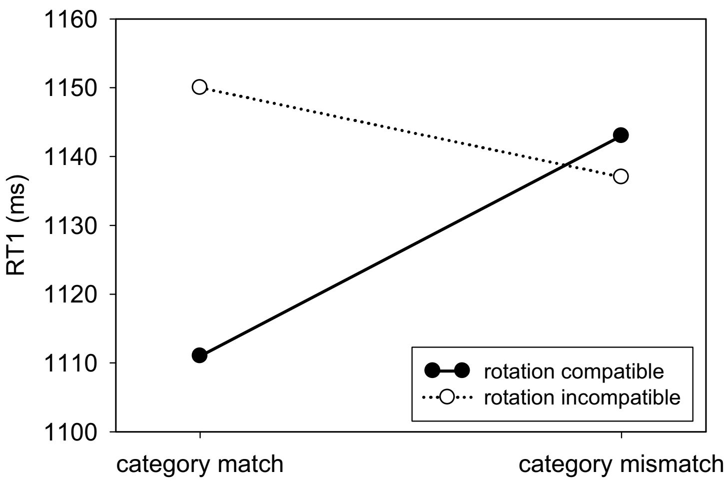

Figure 5.3. The interaction of rotation compatibility and category match on reaction time 1 of Experiment 1

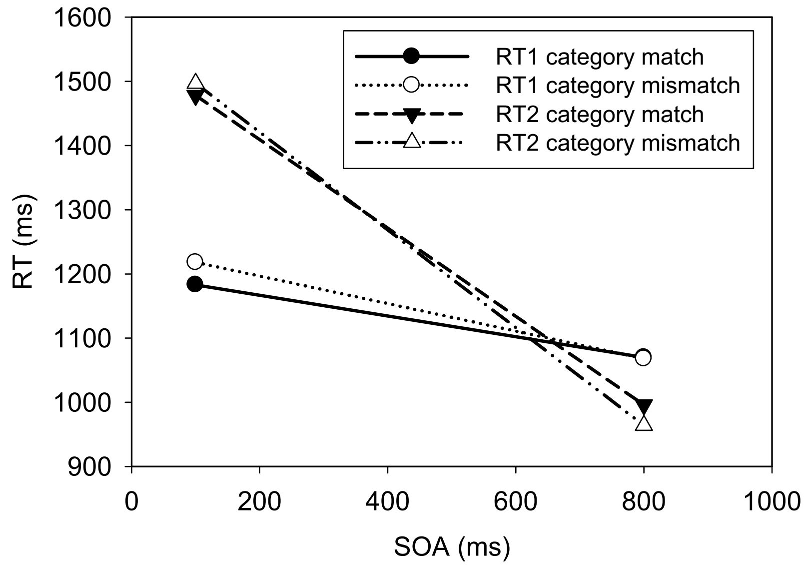

Figure 5.4. The interaction of category match and SOA on reaction time 1 and 2 of Experiment 1

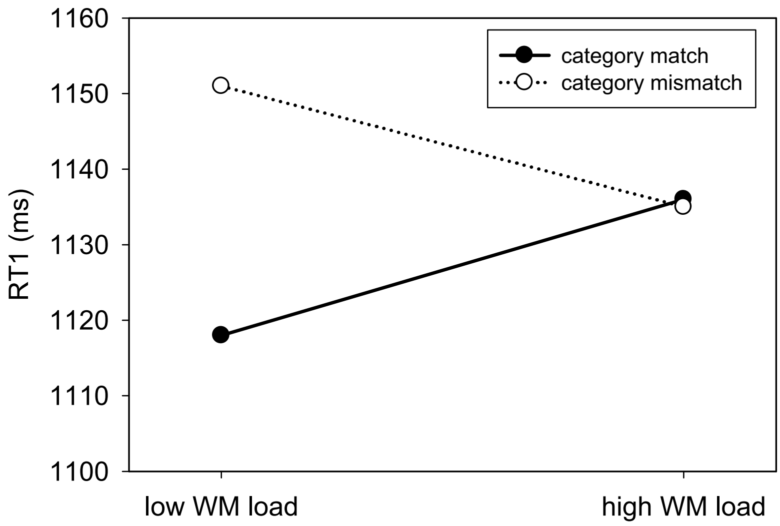

Figure 5.5. The interaction of category match and WM load on reaction time 1 in Experiment 1

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.

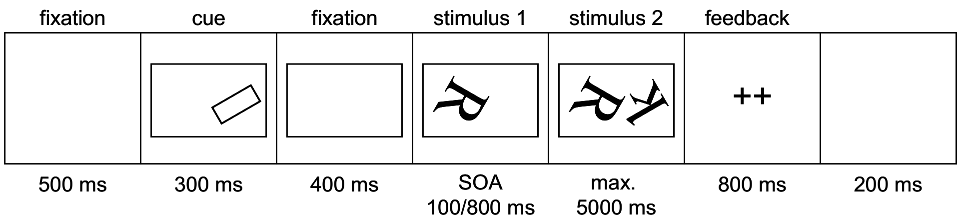

Figure 5.6. Sequence of events within one trial in Experiment 2: The cue is a rectangle that makes a valid prediction of the orientation of the second stimulus in 75% of the trials

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, $t(27) = 1.9$, $SEM = 10$, $p = .071$.

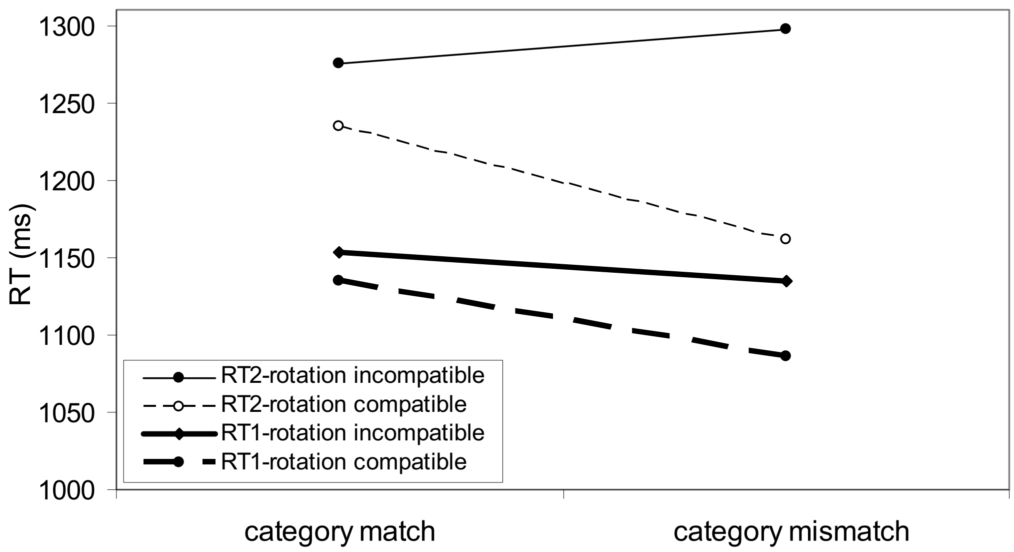

Figure 5.7. The interaction of rotation compatibility and category match on reaction time 1 & 2 of Experiment 2

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, $t(27) = 0.89$, $SEM = 10$, $p = .383$.

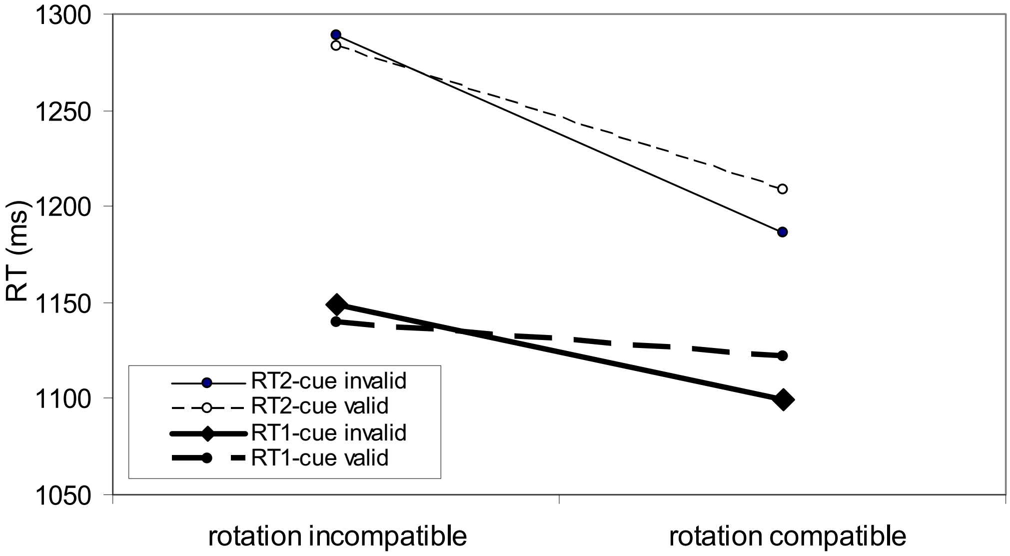

Figure 5.8. The interaction of rotation compatibility and cue validity on reaction time 1 & 2 of Experiment 2

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.