Limitations in dual-task performance

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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.

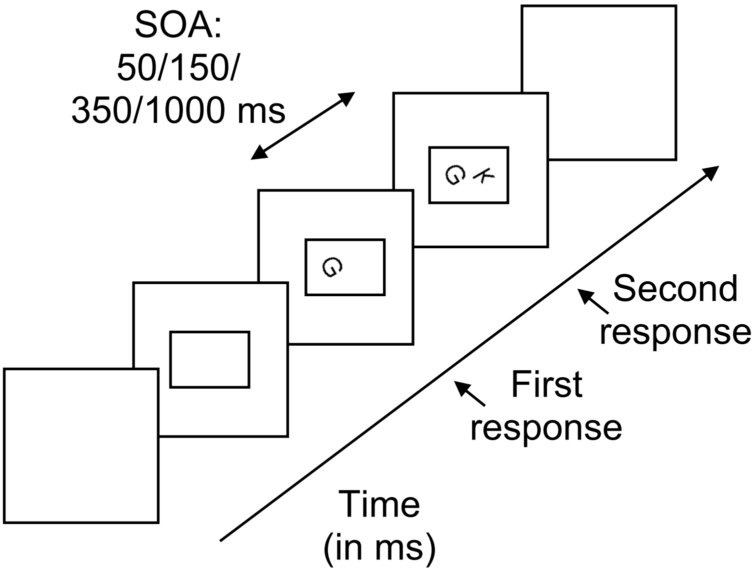

Figure 2.1. Sequence of events within one trial in Experiment 1: the rectangle serves as a fixation, in which S1 appears left from the middle, and after a variable SOA S2 appears right from the middle

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°.

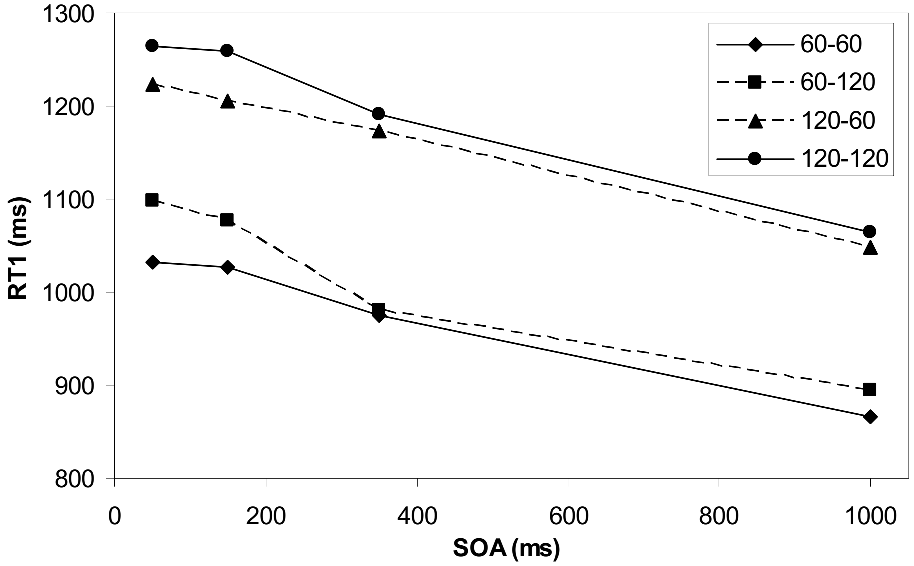

Figure 2.2. The interaction of angle 1, angle 2 and SOA on reaction time 1 of Experiment 1. In this figure, angle 1 and angle 2 are presented in the different combinations that they can occur: both can be tilted 60° or 120°

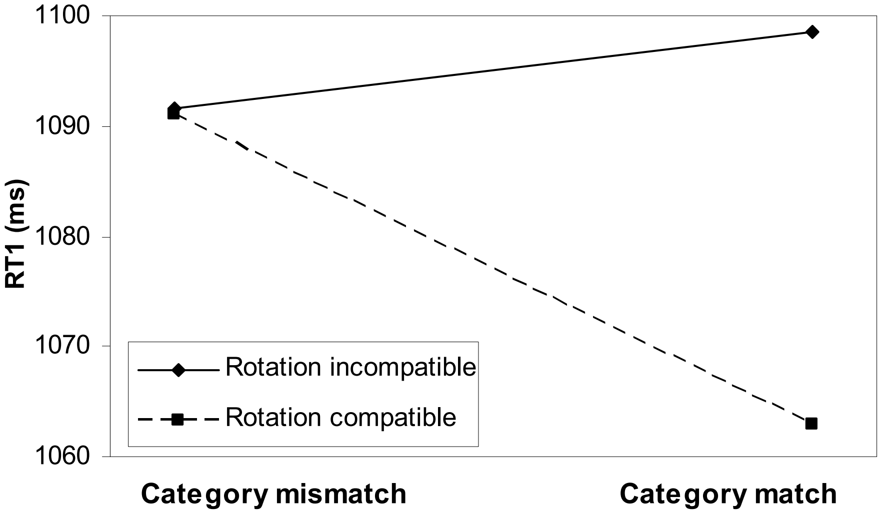

Figure 2.3. The interaction of rotation compatibility and category match on reaction time 1 of Experiment 1

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.

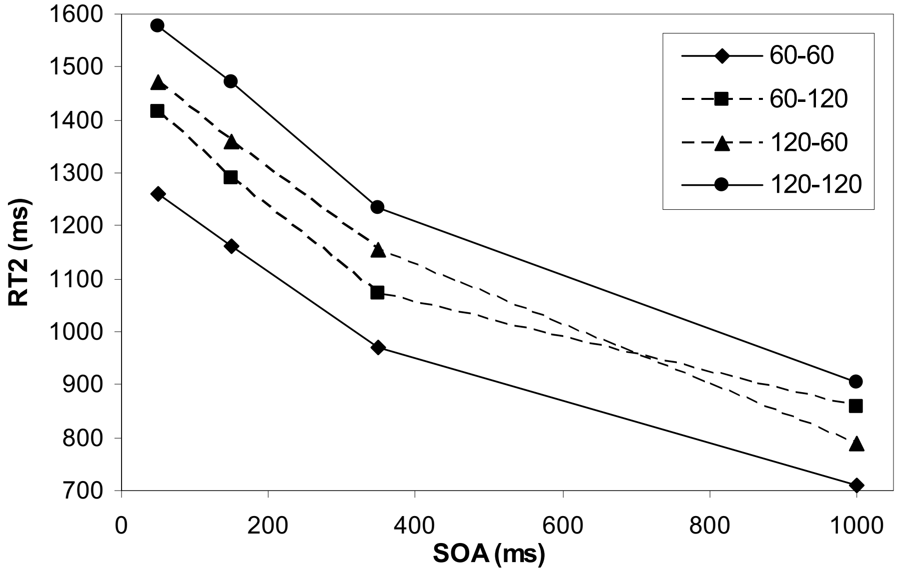

Figure 2.4. The interaction of angle 1, angle 2 and SOA on reaction time 2 of Experiment 1

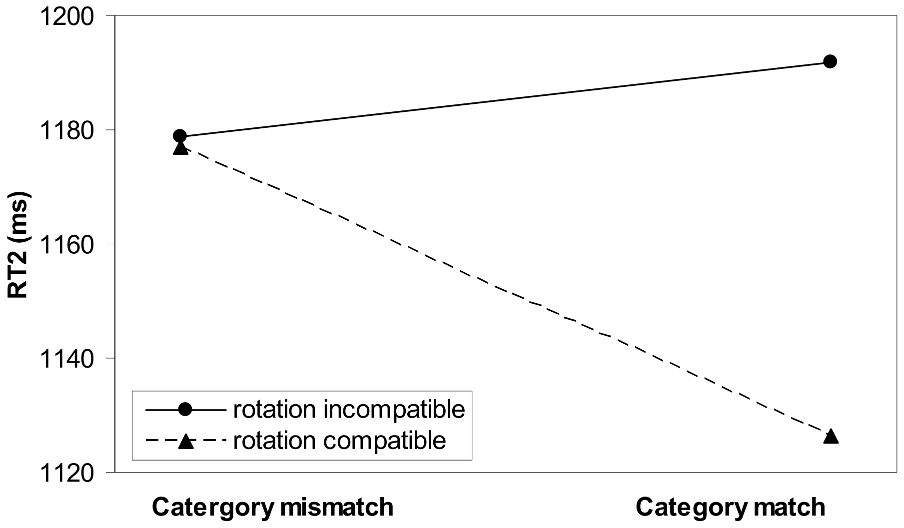

Figure 2.5. The interaction of rotation compatibility and category match on reaction time 2 of Experiment 1

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.

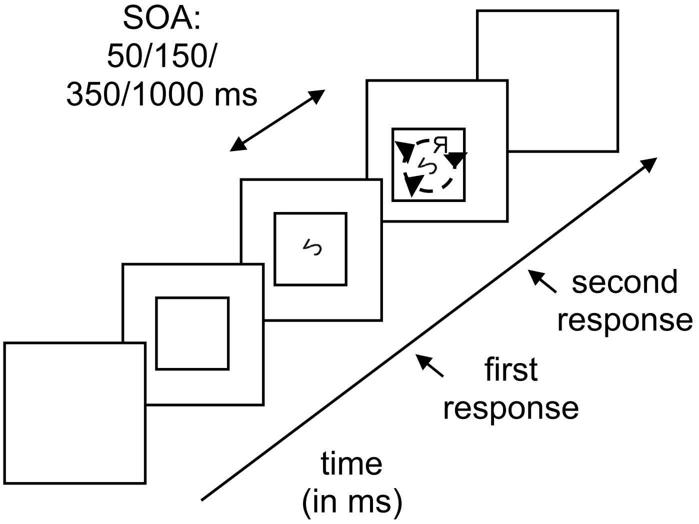

Figure 2.6. Sequence of events within one trial in Experiment 2: the rectangle serves as a fixation, in which S1 appears, and, after a short interval, S2. The arrows indicate circular motion and were not presented in the display

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. η^2	MSE	F	p	part. η^2
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%.

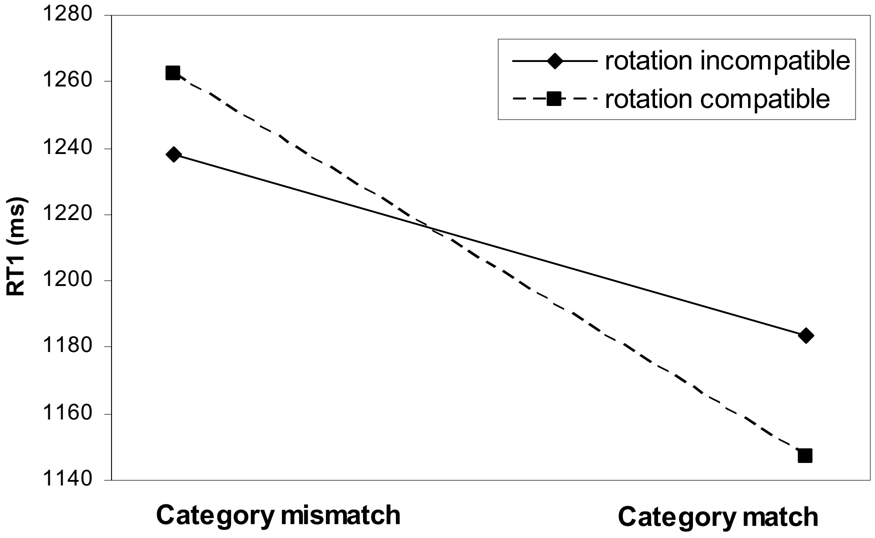

Figure 2.7. The interaction of rotation compatibility and category match on reaction time 1 in Experiment 2

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.