The limits of parallel processing

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Thank you!

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Summary

Doing two things at once should be the fastest and simplest solution for all people that want to manage more in less time. However, there seem to be severe limits for parallel processing. Mostly, when one performs two tasks at the same time, performance of one or both tasks decreases compared to the situation when one performs each task by itself (Pashler, 1984; Ruthruff, Hazeltine, & Remington, 2006; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Van Selst & Jolicoeur, 1994). The present thesis deals with the question to which extent people are able to process two cognitive tasks at the same time and why costs emerge in the majority of cases. Among researchers a strong controversy exists about the limitations of our cognitive system. Generally dual-task interference is taken as evidence for a capacity limitation of our information processing system.

One dominating theoretical model explains interference with a processing bottleneck (Pashler, 1994a). This bottleneck operates at the central response selection stage. This stage is intermediate between stimulus encoding and response execution (Sternberg, 1969). The response selection bottleneck allows only one task at a time to be processed centrally. Is the bottleneck occupied with one task, the next task that arrives at the bottleneck has to wait until it is released by Task 1. This waiting time increases overall processing duration of Task 2 compared to a single-task situation. According to this model stages before and after the bottleneck can be processed in parallel between the two tasks. Therefore, dual-task costs that come up on Task 2 should depend on the duration of the central processing time of Task 1. Moreover, parallel processing is predicted to be not possible. Dual-task costs should be omnipresent whenever the central processing stages of two tasks had to be processed simultaneously.

The bottleneck model has faced some challenges during the last years, because for some task combinations vanished dual-task costs were revealed (Hazeltine, Teague, & Ivry, 2002; Oberauer & Kliegl, 2004; Schumacher et al., 2001) implying that parallel processing is possible. Taking two of these as a starting point the present thesis focuses on factors that are likely to promote parallel processing. For that purpose the thesis examines whether costs reemerge when the similarity between stimulus (S) and response (R) representations of one task is reduced (Experiment 1 and 2) or when the similarity between stimulus and response representations across tasks is increased (Experiment 3 and 4).

The manipulation of similarity in Experiment 1 and 2 is associated with the term of compatibility of stimulus-response (S-R) mappings. S-R compatibility describes the overall level of information transfer between the stimuli and their responses within a task (Kornblum,

Hasbroucq, & Osman, 1990). Low compared to high S-R compatibility is associated with higher top-down control (Kornblum, Hasbroucq, & Osman, 1990). The results showed that it is possible to process two tasks in parallel when both contain a non compatible S-R mapping. Nevertheless, Experiment 1 and 2 also showed that the overall parallel-processing ability is reduced when both tasks contained a non compatible S-R mapping compared to a situation where at least one tasks contained a compatible S-R mapping. This difference in dual-task costs could not be explained by the difference in single-task reaction times for compatible compared to non compatible S-R mapping tasks. Hence, the result is contrary to the prediction of the bottleneck account. Instead the difference in dual-task costs was attributed to higher potential of crosstalk between top-down control signals needed for the two non compatible S-R mapping processes. When both tasks contain a non compatible S-R mapping unintentional interactions of their top-down control signals might result. Interactions can lead to the inappropriate application of executive signals of one task to the other task. Consequently this supervision-based crosstalk can lead to task errors. In order to reduce the error potential, crosstalk has to be resolved or prevented at the outset by a serial processing scheme. The resolution or suppression of crosstalk increases the dual-task processing-duration more than what would be predicted on the basis of single-task performance.

Experiment 3 and 4 examined whether dual-task interference is influenced by the content specific characteristics of the two tasks, i.e. the pairings of their S-R modalities. S-R modality-pairings describe the fact that certain input and output modalities share a representational format (Wickens, Sandry, & Vidulich, 1983). Thereby, manual responses and visual stimuli share the representations of spatial coordinates and vocal responses and auditory stimuli share the representation of sound. Recent results have shown that input-output modality-pairings between stimuli and responses influence dual-task costs. The combination of a visual-manual and an auditory-vocal task were found to produce lesser costs than the combination of an auditory- manual together with a visual- vocal task (Hazeltine & Ruthruff, 2006; Hazeltine, Ruthruff, & Remington, 2006; Ruthruff, Hazeltine, & Remington, 2006; Stelzel, Schumacher, Schubert, & D'Esposito, 2005). Pairings are defined as Standard in the former and as Non Standard in the latter case. This effect was found to be stronger than the modality pairing effect on the single task reaction times. For Non Standard pairings, there is representational overlap between the S-R modalities across tasks with respect to the spatial and the verbal domain. For Standard tasks the modalities of one task either rely on the spatial or the verbal domain. The absence or presence of representational overlap across tasks is the cause of the modality-pairing effect on dual-task costs. Experiment 3 and 4 tested the hypothesis that representational overlap across tasks promotes content-based crosstalk between two Non Standard modality-pairing tasks which is absent for two Standard modality-pairing tasks. Therefore, representational overlap was varied between the stimulus and response modalities (S-R) and between the central and response modalities (C-R) across four groups. The nature of the C-R pairings contained the overlap between the task relevant stimulus features and the response representation. The overlap due to C-R modality-pairings was in former experiments supposed to be responsible for the observed effects on dual-task costs. This could be disentangled form the overlap due to S-R pairings with the particular task design of Experiments 3 and 4. S-R pairings contained the overlap between less relevant stimulus features and the response. The results clearly showed that the effects of S-R and C-R pairings on dual-task costs were higher than one would predict according to their effects on single-task performance. As predicted C-R pairings had stronger influence on dual-task costs than S-R pairings since the C-R pairings coded the overlap between task relevant features across task representations. This result confirmed the view of representational overlap being the source of modality-pairing effects on dual-task costs. Moreover, for C-R Standard groups dual-task costs were vanished after practice. This strongly supports the view that a qualitative switch in processing from serial to parallel was realized for the C-R Standard groups containing low crosstalk. For the C-R Non Standard groups serial processing was assumed, i.e. crosstalk and a processing bottleneck were present after practice for these groups. Overall the results of Experiment 3 and 4 showed that representational overlap and hence crosstalk between tasks is responsible for modality-pairing effects on dual-task costs. Hence, the process of response selection is modality dependent and not amodal as traditionally assumed. This outcome is not in accordance with the bottleneck account, which predicts dual-task costs to depend on single-task latencies and to emerge at all times when central processing stages of two tasks come into temporal conflict. However, for two task combinations parallel processing could be revealed.

Taken together the results demonstrated that parallel processing is possible since in each experiment presented in the present thesis at least one parallel processor was observed. By this the thesis replicated earlier findings of parallel processing and even extended the bandwidth of tasks showing parallel processing. However, the limits of parallel processing are nevertheless obvious. High representational overlap, low S-R compatibility of both tasks and low practice promote a serial processing strategy. Decreasing representational between-task similarity and increasing within-task similarity through high S-R compatibility gives way to parallel processing after practice. From this viewpoint dual-task costs might be reinterpreted.

Dual-task costs arise not due to the impossibility but due to the possibility of parallelism in processing of two tasks. This potential parallelism gives way to unwanted errors, which can be prevented by the choice of a serial processing strategy. For a theoretical point of view the actual results demand a modification of the response-selection concept from an amodal central process that is applied in most if not all sensorimotor tasks to a representation specific process including the transient binding of features coding task relevant aspects of the stimulus and its response according to the task affordances.

1. Introduction

A fundamental question in psychological science concerns the issue whether or to what extent people are able to perform two or more activities simultaneously. Testing the limits is one way to investigate the different components of our information processing system, their configuration and how they function together. Beside its theoretical relevance the answer to this question has a strong practical implication. Advanced technique confronts people more and more with multitasking challenges. In every day life the employment of computerized navigational aids as well as cell phones conversations while driving demonstrate vitally areas of application. Furthermore, in professional life, for example for such responsible positions as air traffic controllers and aircraft pilots dual-tasking research-results are also highly relevant. In addition, broadening knowledge about dual-task processing will provide better designed man machine interfaces to prevent users from becoming overloaded, optimizing their reaction time and performance accuracy.

Without previous knowledge about the empirical evidence regarding dual-task performance one could speculate on the one hand that the human brain is occupied with so many computations at the same time that, logically seen, parallelism should be a common principle of information processing. On the other hand, it would be quite astonishing if instances of queuing were never observed in a system as complex as the human information processing system. Both views are implemented in current theories of information processing, but there is quite disagreement about their weights. The assumptions of dominant dual-task theories about the generality of queuing vary from mandatory queuing because of an inevitable processing limitation of one task at a time to a flexible and strategic adaptation of the processing overlap of two tasks with potential parallel processing, i.e. no built-in processing limitation.

When two tasks have to be processed at the same time, i.e. when the stimuli of two tasks are presented simultaneously (or in close succession) the vast majority of dual-task research revealed that significant dual-task costs emerge (Carrier & Pashler, 1995; Hommel, 1998a; Lien, Ruthruff, & Proctor, 2005; Nino & Rickard, 2003; Pashler, 1984; Van Selst & Jolicoeur, 1994). Dual-task costs refer to the fact that the processing of at least one of the two tasks takes longer and/ or is less accurate compared to its processing in single-task context.

For some researchers these results led to the conclusion that serial processing is the dominant principle in dual-task situations. Though, the time to perform both tasks together was typically found to be shorter than the sum of both single-task times (Welford, 1952). Consequently, serial processing cannot comprise the whole information processing stream, but rather a specific stage or stages (Pashler, 1984, 1994a). A simplified framework of human cognition assumes information processing as a sequence of more or less discrete processing stages (Sternberg, 1969). For most tasks used in the dual-task literature these stages involve stimulus encoding, response selection and response execution. The origin of serial dual-task processing was narrowed in experiments to the central process of response selection (McCann & Johnston, 1992; Pashler & Johnston, 1989, 1998) although pre-and post selectional loci (Broadbent, 1958; Karlin & Kestenbaum, 1968) and even multiple loci (De Jong, 1993) have been discussed.

Nevertheless, there are a few experimental exceptions demonstrating minimal to vanished dual-task costs (Allport, Antonis, & Reynolds, 1972; Göthe, Oberauer, & Kliegl, 2007; Hazeltine, Teague, & Ivry, 2002; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Oberauer & Kliegl, 2004; Schumacher et al., 2001; Shaffer, 1975). They claim that parallel processing of the central response selection stages of two tasks is possible. However, not only the frequency of these results but also the variety of tasks or task combinations for which vanished costs were observed is rather limited relative to the task combinations for which costs were observed.

1.1. The present thesis

The aim of the present investigation is to gain insight in the question why significant dual-task costs emerge so frequently in comparison to the few exceptions showing minimal to vanished costs when performing two tasks. The general outline of the investigation was to examine the limits of parallel processing, by particularly focusing on those task combinations that that already were shown to reach paralell processing. High similarity between the stimulus and the response is one factor facilitating minimal dual-task costs (Greenwald & Schulman, 1973; Levy & Pashler, 2001; Lien, Ruthruff, & Johnston, 2006). Hence, I adjusted experimental designs usually demonstrating vanished dual-task costs, decreased the similarity between the stimulus (S) and its response (R) of one or both tasks, and tested whether costs increased again.

Similarity was manipulated by changing S-R compatibility or S-R modality-pairings. These are two closely related concepts referring to representational aspects of the stimulus and its response. Thereby, S-R compatibility describes the overall level of information transfer between the stimuli and their responses, whereby a high transfer of information implies a high compatibility and vice versa. S-R modality-pairings describe a certain aspect of the overall information transfer, i.e. the fact that certain input and output modalities share the representational format (Wickens, Sandry, & Vidulich, 1983), whereby manual responses and visual stimuli share the representations of spatial coordinates and vocal responses and auditory stimuli share the representation of sound. In the present thesis the effects of S-R compatibility and modality pairings on parallel processing ability were examined in different experiments.

Following this introductory chapter, the thesis is organized into five major chapters. The Chapters 2 to 5 contain the presentation of the four experiments, which are discussed in Chapter 6. The thematic structure of the experimental section is twofold. In Experiment 1 and 2 I focus on the compatibility between the stimulus and its response as a potential factor influencing the parallel processing ability of two tasks. Experiment 3 and 4 regard with the question whether parallel processing is limited to particular S-R modality-pairing combinations.

In the following I will briefly review the major theoretical accounts depicting dual-task performance. First, the bottleneck theory (Pashler, 1994a; Welford, 1952) originally formulated by Welford and later extended by Pashler is introduced. Second, the resource sharing account (Kahneman, 1973; McLeod, 1977; Navon & Gopher, 1979; Navon & Miller, 2002; Wickens, 1980) followed by third the human information processing architecture of the executive-process interactive- control (EPIC) model (Meyer & Kieras, 1997a, 1997b) are presented. Additionally, different experimental paradigms are sketched that are closely linked to a particular theoretical account.

1.2. The Bottleneck theory

The underlying assumption of the bottleneck theory is that queuing is the prevailing principle dominating dual-task performance (Pashler, 1994a; Welford, 1952). Queuing is a process due to the so called bottleneck- a hard wired structure in our cognitive system (at least in the original formulation of the theory). The bottleneck limits information processing to one task at a time. In the early formulation of the “single channel” bottleneck Welford unspecificly stated its locus between perceptual analysis and response execution (Welford, 1980). However, subsequent research narrowed its locus to the central processing stage that is responsible for the translation of the stimulus to its response. Moreover, it was found to include computations as memory retrieval of words, encoding into short-term memory, mental rotation and lexical access (Allen, Lien, Sanders, & McCann, 2002; Carrier & Pashler, 1995; Jolicoeur & Dell'Acqua, 1999; Van Selst & Jolicoeur, 1994). In the case of conflicting central processing stages one has to wait for completion of one task, which had entered the bottleneck first. Processing of one task has to be completed before processing of the other task can start. The second task has to wait. Hence, reaction time (RT) to the task that entered the bottleneck second is usually increased in dual-task context compared to its RT in single-task context.

Testing the predictions of the bottleneck theory is closely connected to the psychological refractory period paradigm (PRP paradigm). The methodology and the term trace back to Telford (Telford, 1931). Although the analogy to the refractory period of neurons is flawed the label established itself. In the typical PRP experiment two tasks were presented. Suppose, for example, a letter discrimination task with a manual response and a tone discrimination task with a vocal response must be performed together. The onset of both stimuli, the letter and the tone are separated in time by a various stimulus onset asynchrony (SOA). The SOA varies from short to long across trials. The variation of SOAs produces strong up to no temporal overlap in the processing of the two tasks. The participants are typically instructed to respond in the order of stimulus presentation, whereby presentation order results in the labeling of Task 1 (e.g., letter task) and Task 2 (e.g., tone task). Additionally, Task 1 is often particularly emphasized. Subjects are instructed to respond as quickly as possible after its stimulus presentation. This should prevent participants from response grouping (withholding Task 1 until Task 2 processing is ready) and from reversal of processing order especially at short SOAs.

The RTs of the two tasks are recorded. What can be observed is a delayed reaction for Task 2 at short SOAs in comparison to long SOAs, which is referred to as the PRP effect. The PRP effect is the hallmark of the bottleneck theory. It comprises up to several hundred milliseconds and has been documented for a variety of tasks (for a review see Pashler, 1994a). However, the RTs of Task 1 do not vary with SOA. Figure 1.1a shows an idealized picture of the relation between SOA and RT for Task 1 and Task 2. Whereas SOA affects the RTs of Task 2, it has no effect on Task 1.

Figure 1.1b depicts the tasks within the PRP paradigm decomposed into stimulus encoding stage, response selection stage and response execution stage. According to the central processing bottleneck idea, only the central stages comprise a processing bottleneck. Processing in all other stages can occur in parallel. At short SOAs this leads to a conflict of the response selection stages of the two tasks. Task 1 had entered the bottleneck already when Task 2 arrives. Task 2 processing has to wait and therefore is postponed until the selection of Task 1 response is ready. With long SOAs there is no conflict for the response selection stages. Task 2 arrives the bottleneck when the central processing of Task 1 is already finished. As a result, the processing of Task 2 is not delayed. Processing of Task 2 at the longest SOA should not be different between dual- and single-task conditions. Therefore, dual-task costs can be calculated by subtracting the RT of Task 2 at the longest SOA from the RT of Task 2 at the shortest SOA (RT2 (SOAshort)– RT2 (SOAlong)).

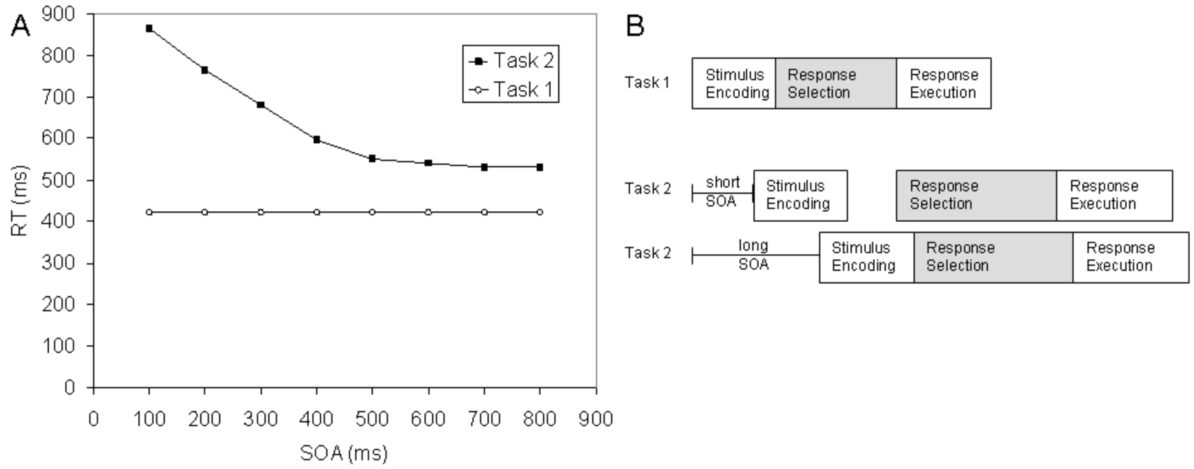

Figure 1.1. The PRP effect. The left side (a) shows RTs for Task 1 and Task 2 from a hypothetical PRP experiment as a function of SOA. Task 2 RTs are increased at short SOAs compared to long SOAs (PRP effect). Task 1 does not show a SOA dependency. The right side (b) shows a stage model of the bottleneck theory as the explanation of the PRP effect. At short SOA response selection of Task 1 occupies the bottleneck when Task 2 is already ready to enter it. Task 2 response selection has to wait. At long SOA no processing delay emerges for Task 2. Response selection of Task 1 is finished when Task 2 is ready to enter the bottleneck.

One prediction of the bottleneck theory is that the slope of the RT2 at the lower range of the SOAs approaches -1. At short SOA, when the central processing stages of both tasks come into conflict the central processing of Task 2 is delayed. Delaying central processing of Task 2 by 100 ms should full size propagate to an increase of RT2 of 100 ms. At long SOA, when the central processing stages of the two tasks no longer come into conflict, Task 2 is not delayed. For those SOAs the latency function of RT2 should show a flat slope and should parallel latency for Task 1.

1.3. Resource sharing accounts

An alternative to the central bottleneck idea represents the resource theory. Just as in the bottleneck idea resource theorists assume a fixed and therefore limited capacity that is needed for central processing. But contrary to the bottleneck idea, the resource theorists postulate that this capacity can be shared by the central processes of different tasks and processes can take place in parallel (Kahneman, 1973; McLeod, 1977; Navon & Gopher, 1979; Navon & Miller, 2002; Wickens, 1980, 1984). Nevertheless, parallelizing does not come without disadvantages. Dual-task costs will arise, if the joint resource demand of the different tasks exceeds the available supply. The allocated capacity to each task is assumed to be proportional to its processing rate. Capacity allocation happens in a graded fashion and can be allocated in any ratio in order to meet the current task demands or personal preferences. Higher task difficulty, for example can cause an allocation ratio in favor of the more difficult task compared to an easier task in a dual-task situation. Hence, in most of the possible cases the processing rate of both tasks is lowered compared to their processing rate when performed in single-task context.

However, one extreme case of resource allocation would be a proportion of 100: 0 (Task 1: Task 2). The central processing of one task exclusively receives all of the capacity and the other task does not receive any resource contingent for central processing. Under this allocation ratio, one task is processed at its normal rate but the other one is delayed. This particular resource-allocation ratio mimics a serial central processing bottleneck. The explicit Task 1 emphasis in the instruction of the PRP paradigm, for example, should encourage participants to spend the full resources on Task 1. With these assumptions formal central resource sharing models (Navon & Miller, 2002; Tombu & Jolicoeur, 2003) recently have shown that they are perfectly able to simulate the predictions in line with the bottleneck account and hence can account for the effects observed within the PRP paradigm.

However, some researchers have questioned the existence of a single resource pool and proposed instead multiple, independent resources (Gopher & Navon, 1980; Navon & Gopher, 1979; Wickens, 1984). The concept of multiple resources was, for example, formulated by Wickens and colleagues (Wickens, Sandry, & Vidulich, 1983). According to this view separate resource pools exists for processing different stimulus modalities (visual vs. auditory), different central domains (spatial vs. verbal) and different response modes (manual vs. vocal). When two tasks demand separate resource pools, efficient time-sharing and little to no interference is expected.

A persistent problem with the idea of resources is the low theoretical precision of the resource concept, which is closely connected to its quantification. Having no clear-cut, generally accepted definition for a resource (Navon, 1984; Oberauer & Kliegl, 2001; Pashler, 1998) makes it difficult to adequately operationalize resources (Salthouse, 1988) and hence makes it difficult to evaluate specific hypotheses. This led the resource concept become empirically empty.

1.4. The Executive-process interactive-control model

Meyer and Kieras (Meyer & Kieras, 1997a, 1997b) formulated a further theoretical approach explaining dual-task performance. They postulated a cognitive architecture within which human information processing can be simulated: the executive-process interactive-control model (EPIC). Their theory challenges accounts assuming a divisible or indivisible limitation of central capacity .Their basic assumption is that no central capacity limitation per se exists in the human information processing. The amount of temporal overlap between the processing stages of two tasks depends on the task scheduling strategy that is flexibly controlled by executive processes. The application of a daring strategy causes high temporal overlap between tasks and low dual-task costs. The application of a cautious strategy causes low temporal overlap and high dual-task costs. According to Meyer and Kieras several preconditions have to be fulfilled to promote the choice of a daring task overlapping strategy: a) the tasks have to be equally emphasized with no specification of response order b) the tasks must not overlap in sensory or motor stages, c) combined practice of both tasks is necessary. Fulfilling these preconditions parallel processing can be induced. According to the authors the vast majority of dual-task interference traces back to the violation of one or more of the postulated preconditions for parallel processing. Hence, in these cases the two tasks are scheduled serially and dual-task costs emerge. One special claim of Meyer and Kieras is that the explicit and implicit affordances to the participants in the PRP paradigm induce a serial processing strategy. From the viewpoint of EPIC it is suboptimal to instruct participants to respond to the stimuli in order of presentation and to give Task 1 priority. According to EPIC this instruction causes the SOA effect for Task 2. Participants might weight Task 1 as more important, i.e. needs to be processed first. To fulfill task instructions participants are motivated to delay Task 2. The application of a serial processing strategy within EPIC can mimic the characteristics produced by a central bottleneck, which has already been successfully simulated (Meyer et al., 1995).

One dual-task paradigm that does not promote a serial processing strategy is the simultaneous presentation paradigm (SPP). In the SPP the stimuli of the two tasks are always presented at the same time, setting the SOA to zero. Hence, merely due to the temporal presentation order of the two stimuli no task can be defined as Task 1. This should reduce the probability of utilizing a delay strategy for Task 2 that can be involved in the PRP paradigm according to Meyer and Kieras. Dual-task costs were calculated as the difference between the RTs of one task in the dual-task condition and the RTs of this respective task in a single-task condition. In the single-task condition the two single tasks are usually randomly intermixed. From the viewpoint of EPIC, the SPP paradigm is the preferred tool to induce a parallel processing strategy.

Nevertheless, dual-task costs were observed when the design met the claimed requirements by Meyer and Kieras, e.g., both tasks were given equal priority and no restriction in response order was specified (Levy & Pashler, 2001; Pashler, 1994b; Ruthruff, Pashler, & Klaassen, 2001), extensive practice opportunity was given (Ruthruff, Johnston, & Van Selst, 2001; Van Selst, Ruthruff, & Johnston, 1999), or minimal sensory and motor overlap between the two tasks was realized (Levy & Pashler, 2001). However, none of these studies met all requirements of Meyer and Kieras in one experiment.

Schumacher et al. (2001) conducted the first study that conjointly implemented all three preconditions. Indeed, the authors showed that the dual-task costs in RTs were eliminated for two tasks. Although minor costs in errors remained after practice, the authors concluded that (at least for some participants) response selection of both tasks proceeded in parallel, supporting the view of Meyer and Kieras (1997a). In a series of experiments Hazeltine and colleagues (Hazeltine, Teague, & Ivry, 2002) replicated the results of Schumacher et al. and confirmed the basic finding of parallel dual tasking.

However, Tombu and Jolicoeur (Tombu & Jolicoeur, 2004) challenged the interpretation of parallel processing by the Schumacher et al. and the Hazeltine et al. studies due to methodological aspects. They reviewed the response deadline procedure used in Schumacher et al. (2001) and observed that the deadline was adjusted to the dual-task condition only, which might have encouraged the effort in dual tasks but not in single tasks. According to Tombu and Joliceour this has led to an overestimation of the single-task baseline. As a consequence, dual-task costs in Schumacher et al. - calculated as the difference between dual-task and single-task RTs- have been underestimated. Furthermore, Tombu and Jolicoeur criticized the single-task baseline used in the SPP as an inappropriate baseline measurement. Single-task trials of both tasks were randomly intermixed among dual-task trials. The single-task baseline is argued to generally overestimate single-task RTs due to several aspects. Among them the task switching costs, omissions of a stimulus in the case of a single- but not dual-task trial and uncertainty about the type of upcoming task increase single-task RTs compared to blocks in which each task is presented alone throughout one block. This consequently results in underestimated dual-task costs and makes a reliable interpretation of the results impossible. With a revised response deadline method and the more conservative single-task baseline Tombu and Jolicoeur (2001) failed to replicate the finding of perfect time sharing. Therefore, the actual controversy in dual-task research not only contains the question whether parallel processing is possible or not. It also contains a debate about the adequate method examining dual-task performance.

A task paradigm that avoids several disadvantages of SPP and PRP represents the continuous memory updating tasks. This task was traditionally used in the field of working memory research (Oberauer & Kliegl, 2001). However, Oberauer and Kliegl (Oberauer & Kliegl, 2004) applied it to the dual-task research. They combined a spatial with a verbal memory updating task. After practice five out of six tested participants showed parallel processing of these two tasks. This result could be replicated and extended by Göthe, Oberauer and Kliegl (Göthe, Oberauer, & Kliegl, 2007), which used the same memory updating tasks as Oberauer and Kliegl, but a slightly different training schedule.

Several problematic issues can be avoided with the application of the memory updating task: inappropriate response deadlines, the measurement for the single-task baseline, and the implicit affordance of a serial processing strategy. This makes it advantageous over the SPP and the PRP paradigm. The studies using the continuous memory updating tasks (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) represent so far the most unequivocal piece of evidence that two tasks can be processed in parallel.

I therefore, used this paradigm in the present thesis to test for the limits of parallel processing. It was implemented for Experiment 1 and 2, which focus the compatibility between a stimulus and its response of one task as a potential factor influencing its parallel processing ability when combined with another task. Experiment 3 and 4 use the SPP and PRP paradigm, respectively. The experiments examine and compare dual-task costs for different S-R modality-pairing groups. Whereas the SPP paradigm is discussed to be more adequate to induce parallel processing, the PRP paradigm is more adequate to assess dual-task costs, i.e. to test for a bottleneck. Therefore, the different S-R modality-pairing groups practiced their two tasks within the SPP. Additionally; they were transferred to a PRP paradigm and tested for dual-task costs at the end of practice. Hence, the advantages of both paradigms are used to unambiguously assess potential parallel processing.

The twofold thematic structure of the present thesis with examining the S-R compatibility effect on parallel processing in Experiments 1 and 2 and the modality-pairing effect in Experiments 3 and 4 is paralleled by the choice of the experimental paradigm. Whereas Experiments 1 and 2 test for parallel processing with the continuous memory updating paradigm, Experiments 3 and 4 implement the SPP and the PRP paradigm, respectively and integrate their results. In the following for each experiment individually the rationale behind the experimental manipulations and the description of the experimental paradigm is given. Consequently the analyses and the discussion of the results are presented. The final chapter summarizes the obtained results and discusses them.

2. Experiment 1 -Dual-task processing of two memory updating tasks with arbitrary S-R mappings

Parallel processing without dual-task costs after practice has been demonstrated for two memory-updating tasks by Oberauer and Kliegl (2004). This result was replicated by Göthe, Oberauer and Kliegl (Göthe, Oberauer, & Kliegl, 2007) for a subgroup of young participants using a slightly different training schedule but the same task combination of a spatial and a verbal memory-updating tasks. The participants in Brambosch (2003), also provided with two memory-updating tasks, however, were not able to process their tasks in parallel. Different aspects in task design could be responsible for this difference to the earlier observation of parallel processing. The present experiment focuses on the compatibility of stimuli and responses within each of the two tasks.

In the spatial task of Oberauer and Kliegl a dot had to be mentally shifted within a three by three grid in the direction of an arrow displayed on the screen. The verbal task was to update a digit through simple arithmetic calculations according to tones. A high-pitch tone was associated with adding two and a low-pitch tone with subtracting one. After presentation of the initial digit and dot position, seven to nine operations were presented for each stimulus. Participants worked through the sequence of operations in a self-paced manner and thus delivered a corresponding number of updating RTs in each sequence. There were two updating conditions for the verbal and the spatial representations: Updating was either sequential or simultaneous. In the sequential updating sequence the participants received all updating operations of one task first (e.g. the spatial task) followed immediately by the updating operations of the other task (e.g., the numerical). In the simultaneous updating condition the sequences of updating operations were presented simultaneously for both tasks, i.e. the arrow and the tone. Whereas processing of both tasks was clearly sequential in the first condition, parallel processing was indicated for the second condition.

The two updating conditions allow making a prediction for parallel processing in the following way. If perfect time sharing of the two tasks in the simultaneous condition was achieved the duration for completing both operations in the simultaneous condition should have been equal to the longer of the two updating RTs (one spatial and one verbal) in the sequential condition. Hence, maximum RTs in the sequential condition (max(seq)) provide a criterion of parallel processing in the simultaneous condition. If RTs for updating both tasks in the simultaneous condition are longer than the max(seq) criterion, parallel processing has not been reached. This would support the assumption of a central bottleneck that limits performance in the simultaneous condition. The difference between observed RTs in the simultaneous condition and max(seq) RTs defines the dual-task costs. According to the bottleneck account it reflects the slack time that arises when the second operation has to wait for the first to get through the bottleneck. Indeed, in several investigations this difference was found to be zero after practice for most of the young participants (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004), indicating parallel processing.

However, in the experiment of Brambosch (2003), none of the six tested participants yielded vanished dual-task costs. In this experiment Brambosch combined the numerical arithmetic task from Oberauer and Kliegl with a letter arithmetic task. The letter task consisted of the word “LUNA” which represented an endless letter loop within which participants had to jump either one or two letters ahead. The updating stimuli indicating where to jump were coloured dots, whereby a red dot indicated to jump one letter and a green dot to jump two letters ahead from the actual letter position. That means that when the participant had the letter “A” in mind as starting position and had to jump one letter ahead the participants had to go to the letter “L”. Figure 2.1a shows another example of the letter updating.

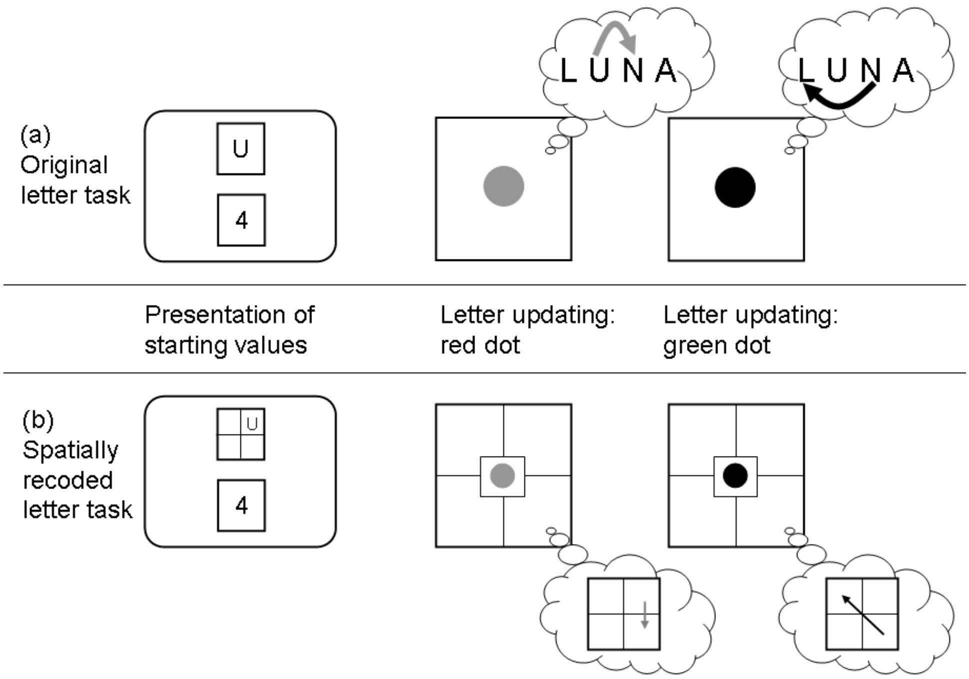

Figure 2.1. Reduced example of the letter task. In the upper row (a) the original and in the lower row (b) the spatially recoded variant is shown. For both variants the presentation of starting values (first box) and the two updating stimuli (second and third box) are presented. (a) For the original task the starting letter is presented in the upper frame of the screen. The updating consists of the presentation of coloured dots. A red dot (here grey) entails an internal shift one step forward within the “LUNA” word loop (illustrated within the cloud next to the stimulus material). The green dot (here black) entails a shift two steps forward within the “LUNA” word loop. (b) For the spatially recoded variant the staring letter is presented in a two by two grid in the upper half of the screen and the updating stimuli appeared in the middle of this grid. The red dot indicated a clockwise shift of the actual spatial location and the green dot a diagonal shift.

At different points in the training schedule (after the third, the sixth or the twelfth block of practice of the two verbal tasks) each of the six tested participants got a spatial recoding of the letter arithmetic task (see Figure 2.1b). For the spatially recoded variant of the letter task each letter of the word “LUNA” was assigned to a fixed location within a two by two grid shown in the upper half of the screen starting with the “L” in the upper left position and continuing clockwise. The updating stimuli were presented in the centre of the grid. The spatial recoding led to the fact that now the red dot indicated a clockwise shift and a green dot a diagonal shift of the actual position within the grid. As in the original variant the final letter was probed. However, in the spatial recoded variant the updating and the internal recall of the final value could be done without knowing the actual the letter identity. It could be solely done on the basis of the spatial location, which could be translated into the letter identity afterwards.

Prior to the introduction of the spatial recoding of the letter task the participants worked on two verbal tasks. Introducing the spatial recoding of the letter task should test whether dual-task processing of two tasks relying on different domains within the working memory, i.e. the verbal and the spatial domain (Baddeley, 1986, 2000; Henson, 2001; Jonides et al., 1996; Logie, 1995) leads to higher parallel processing compared to the situation where the two tasks rely on the same domain, i.e. the verbal domain. If participants had used the spatial recoding of the letter task the experiment of Brambosch similarly to Oberauer and Kliegl included a spatial and a verbal task. Hence, one could assume that after the recoding similar results with respect to the parallel processing ability could have been reached by the participants of Brambosch compared to the participants of Oberauer and Kliegl. The individual practice courses indeed showed that the spatial recoding led to a significant decrease in dual-task costs for most of the participants. In contrast none of the participants was able to effectively eliminate dual-task costs as seen in Oberauer and Kliegl. This was even true for the participants that got the recoding very early, which meant that they could practice most of the time with the spatially recoded letter task.

What can be responsible for this difference? On the one hand this can be due to the letter task still relying on verbal codes. The initial and the final values that had to be memorized and to be reproduced were the letters of the word “LUNA”. While updating the participant could still associate each grid location with a letter. Although this was not mandatory, it can’t be ruled out and could have led to the fact that still both tasks relied on verbal features even after the recoding was introduced. This can have deteriorated the parallel processing ability.

On the other hand along with the adaptation of the task modalities also the nature of the S-R mapping of the letter task was changed from Oberauer and Kliegl to Brambosch. This also applies to the spatially recoded variant of the letter task. While in Oberauer and Kliegl (Oberauer & Kliegl, 2004), as in Göthe, Oberauer and Kliegl (Göthe, Oberauer, & Kliegl, 2007) the spatial task employed arrows to shift the spatial position, in the experiment of Brambosch coloured dots were used. Thereby, the former assignment constitutes a so called congruent S-R mapping and the latter an arbitrary S-R mapping. The present experiment tries to close the gap between the results of Brambosch and Oberauer and Kliegl by examining this second possibility that the S-R mapping was responsible for the different outcomes using a spatial and a verbal task.

What are S-R mappings and why might they play an important role for the dual-task performance? S-R mappings are mainly investigated in single-task context (Fitts & Seeger, 1983) and generally describe the level of information transfer, i.e. the compatibility between the stimuli and their responses due to their representational overlap. S-R mappings are divided into compatible, incompatible and arbitrary mappings (Kornblum, Hasbroucq, & Osman, 1990). The compatible S-R mapping includes the highest transfer of information between processing of the stimulus and selection of the appropriate response (e.g. pressing a left response key according to a light flash presented at the left side, respectively, a right response to a right flash). No transfer is possible for an arbitrary S-R mapping (e.g. pressing a left response key according to a green light flash, respectively, or a right response key according to red coloured light flash). Incompatible mappings are somewhere in between the compatible and the arbitrary mapping (e.g. pressing a right response key according to a left presented, i.e. mirrored light flash, respectively, pressing a left response key according to a right presented light flash). For the incompatible mappings stimulus and response share informational overlap (in the example the spatial domain), but a more or less simple rule has to be applied to select the correct response, i.e. not the compatible one.

Here it becomes obvious that the different levels of S-R compatibility are closely connected to different levels of top-down control influencing the selection of the appropriate response (Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990). With a compatible S-R mapping the stimulus representation alone activates a response that corresponds to the required response. Top-down control does not necessarily play a crucial role for response selection. In contrast, with an incompatible S-R mapping the incorrect compatible response is pre-activated by the stimulus and creates a conflict that needs top down control to get solved (Kornblum, Hasbroucq, & Osman, 1990). In the case of arbitrary mapping there is no overlap between activated stimulus and response representations. Here, top-down control is required to select the appropriate response according to a stimulus. The information carried by the stimulus representation alone does not benefit (or hinder) selection of the appropriate response.

The numerical arithmetic task, which was identical for all studies (Brambosch, 2003; Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004), involved an arbitrary S-R mapping as the tones did not inherently carry the information needed for the mental arithmetic. One could argue that adding and a high pitch tone on the one hand and subtracting and a low pitch tone on the other hand might share the representation within an up-down dimension. But the absolute value of counting up and down, i.e. two steps up and only one step down, could not be directly inferred from the tone. Therefore, there was at least very low information transfer between the tone and the calculation processing which demands executive top-down control. As mentioned above the spatial task used in Oberauer and Kliegl and the Göthe et al. study (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) had a compatible S-R mapping. Here, the information of the direction indicated by the arrow cued directly the shift of the dot position within the grid. Hence, the requirement of top-down control was minimal, at least after some practice. For the letter task in Brambosch (being either verbal in nature or spatially recoded) the S-R mapping was arbitrary. There was no information transfer between the colour of the dot and the mental shift that had to be applied. Hence, for the Brambosch experiment two tasks with arbitrary S-R mappings were combined. The S-R mappings in the Oberauer and Kliegl and the Göthe et al. (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) study can be categorized as compatible (spatial task) and arbitrary (verbal task).

Why should the combination of S-R mappings affect the dual-task performance? Oberauer and Kliegl (Oberauer & Kliegl, 2004) supposed that for their tasks (spatial and verbal) the qualitative switch from serial to parallel processing could be accomplished to the degree that the implementation of S-R mapping rules becomes autonomous of top-down control signals. Control signals set parameters (Logan & Gordon, 2001) for the application of S-R mapping rules. The implementation of two S-R mapping rules at the same time increases the potential of crosstalk, i.e. the confusion between the executive control parameters (Duncan, 1986; Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Norman & Shallice, 1986). This implies that the control signals of one task could be applied incorrectly to the other task, creating error potential when two tasks are combined.

The term of crosstalk is typically used to refer to situations with informational or representational code overlap between the representations across tasks that are held simultaneously in working memory (content-based crosstalk). The code overlap introduces the potential of code confusability, rather than a mutual degradation of each task representation. In the present context crosstalk is used in a broader scope as supervision-based crosstalk. It describes the potential of confusion of executive control signals monitoring each task (Duncan, 1986; Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Norman & Shallice, 1986).

Generally, high crosstalk degrades dual-task performance, relative to a situation where low or no confusion between tasks is existent (Koch, 2009). Thereby, crosstalk produces a “binding problem”, i.e.the problem to define which response goes with which stimulus (Logan & Gordon, 2001, p. 398). In their executive-control model of dual-task performance Logan and Gordon (Logan & Gordon, 2001) propose that the binding problem can be solved though a serial processing mode of the two tasks. When both tasks are no longer processed simultaneously the potential of confusion is lower. This should prevent potential errors associated with the crosstalk.

For the task combination used in Oberauer and Kliegl, the potential for crosstalk was minimal. The content-based crosstalk could be reduced to a minimum since they used two dissimilar tasks from different working memory domains, one spatial and one verbal. Furthermore, the combination of a compatible S-R mapping (spatial task) and an arbitrary S-R mapping (verbal task) kept the potential of supervision-based crosstalk low since only the implementation of the arbitrary S-R mapping had to run under top- down control. Oberauer and Kliegl interpreted that with the right task combination the dual-task binding-problem does not arise. The shift from serial to parallel processing with practice can be reached.

The aim of the present study is to test whether parallel processing of two tasks is still possible when both tasks contain arbitrary S-R mappings, requiring top-down control. Therefore, the verbal-numerical task of the Oberauer and Kliegl (2004) study is kept unchanged. The second task is the spatially recoded variant used in Brambosch with minor changes. The positions within the two by two grid are not associated with any letters in the actual experiment. Instead the initial position is indicated by a dot. The coloured cues to shift the dot position are kept. Hence, there are two changes in the spatial task compared to Oberauer and Kliegl: The S-R compatibility of the spatial task and the size of the grid. Both influence task difficulty. S-R compatibility of the present spatial task is lower in comparison to the Oberauer and Kliegl study, which should make it more difficult. In contrast the smaller grid (two by two vs. originally a five by five grid) is one factor that should make the task easier compared to Oberauer and Kliegl. Thus, their effects on task difficulty possibly compensate each other. A difference in dual-task performance between the present and earlier experiments (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) consequently should not be attributable to task difficulty per se. The increased requirement of top-down control for the arbitrary S-R mappings of the verbal and the spatial task in the present experiment rather should increase the potential of supervision-based crosstalk between the tasks. If supervision-based crosstalk influenced the result in Brambosch the selection of a serial processing strategy also should be more frequent for the present compared to the task combination used in Oberauer and Kliegl.

2.1. Method

Participants. Nine Participants (one male) from the University of Potsdam were tested. They had a mean age of 24 years (range: 19 and 30). Participants were paid six Euro per session plus a bonus depending on accuracy and speed.

Design and Procedure. Two continuous memory-updating tasks, a spatial and a numerical were combined to test for parallel processing. In the case of the numerical task the participants had to do elementary arithmetic calculations in the range of one to nine starting from an initially presented digit. The participants had to calculate according to two presented tones (800 Hz and 200 Hz) indicating adding two or subtracting one. The spatial task consisted of mentally shifting the spatial position of a dot within a four fielded grid. The direction of the demanded dot movement could be either a diagonal or clockwise shift. The direction of the shift had to be inferred from the colour of a larger dot following a previously instructed assignment. The colour red announced a clockwise shift from the actual position of the dot and the colour green a diagonal shift. After the presentation of the starting values for both tasks (a digit and a dot position), the updating sequence started with the presentation of seven to nine successive updating operations per task (tones and colours). Participants worked through the sequence in a self-paced manner. There were two updating conditions- the sequential and the simultaneous. In the sequential condition the participants first completed a sequence of updating operations of one task (e.g. the numerical) before the updating sequence of the correspondent other task (spatial) started. In the simultaneous condition one updating stimulus of each task (a tone for the numerical, a coloured dot for the spatial task) were displayed concurrently during the updating sequence.

Figure 2.2 depicts one procedural trial. At the beginning of each session the task condition (whether sequential or simultaneous) was presented on the screen. There were no explicit practice trials although I regarded the first five trials of each session as practice trials and thus excluded them from further analysis. At the beginning of a single trial the participant saw the German word for “ready” (“Achtung”) for 500 ms in black on the white screen before the screen went blank for 500 ms. A trial consisted of three parts, the successive presentation of initial starting values of both tasks, the sequence of updating operations of both tasks (sequential or simultaneous), and successive probing of final values of both tasks. The starting values of the two tasks were presented in random order. The starting value of the numerical tasks was one randomly chosen digit in the range of one to nine shown in a frame in the lower half of the screen. The starting value for the spatial task was a black dot randomly presented in one of four possible locations in the two by two grid shown in the upper half of the screen. The starting value of each task remained on the screen until the participant pressed the space bar, which in turn initiated the updating phase. In the case of a sequential updating one updating sequence of seven to nine updating cycles (one cycle is one operation of the respective task) of one task was followed by one updating sequence of seven to nine updating cycles of the other task. For the updating phase of the simultaneous condition only one updating sequence of seven to nine updating cycles was presented. In the simultaneous condition one updating cycle included simultaneous presentation of both types of updating stimuli. Task order (spatial or verbal) was randomized in the sequential condition. Presentation of the updating stimuli was self-paced by pressing the space bar. The updating stimulus (in the sequential condition) or the updating stimuli (in the simultaneous condition) had to be applied immediately to the value of the corresponding task. The result had to be kept in mind as input for the next updating operation. The press on the space bar immediately caused the display of the next updating stimulus (sequential condition) or pair of stimuli (simultaneous condition). For the numerical task the updating stimuli were tones. The high pitch tone indicated to add two to the actual number and the low pitch tone indicated to subtract one from the actual number. For the spatial task the updating stimuli was a coloured circle shown in the middle of the two by two grid.

The red colour indicated to shift the actual position of the dot one step further in clockwise direction and the green colour to shift it diagonally. After the updating phase the result of both updating tasks had to be recalled. Recall of the numerical task was by typing the digit via the PC keyboard. In the spatial task the four positions of the grid were matched spatially compatible onto four key of the numeric keypad, respectively the digits one, two, four, five, and recall was by pressing the associated position key. To avoid the encouragement of coding the positions in a numeric way stickers covered the actual keys. Accuracy feedback was given for each task after each trial.

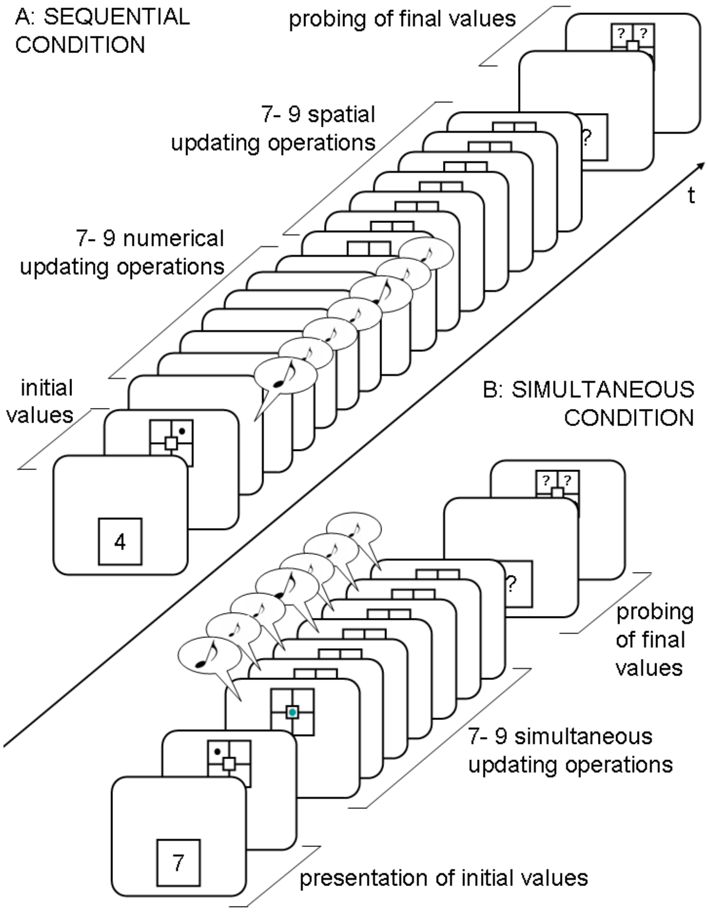

Figure 2.2. Design of the memory updating paradigm with the spatial and verbal tasks. The upper left part of the figure (a) shows an example of the sequential updating condition. The lower right part of the figure (b) shows an example of the simultaneous updating condition.

The participants were instructed that bonus points were given for fast and accurate responding. For one bonus point the participant got 0.05 Euro reward additionally to their normal payment. They earned one bonus point for each percentage correct above 90% and lost one bonus point for each percentage correct below 90%. Five points were assigned for the mean RT of the actual session that felt below the mean RT of the preceding session of the same updating condition. Five points were subtracted for a mean RT of the actual session that exceeded the mean RT of the preceding session of the same condition. At the end of a session the acquired bonus points, the mean accuracy RTs for each task were displayed.

The participants trained the two tasks for 24 to 30 sessions. One session lasted 30-45 minutes. One session consisted of 80 trials of one updating condition. The order of updating conditions alternated between sessions and was counterbalanced between participants. Two consecutive sessions containing one sequential and one simultaneous condition were regarded as a training block.

2.2. Results

All participants trained for at least twelve blocks. For participants A-E[1] the mean dual-task costs (calculation explained below) for the eleventh and/ or the twelfth training block fell below 100 ms. For participants F-J the mean dual-task costs for the eleventh and/ or the twelfth training block exceeded 100 ms by about 50 to 200 ms. As the data of participants A-E seemed promising for eliminating dual-task costs, they further received three training blocks. They therefore trained for a whole of 15 blocks. The other participants stopped training after their twelfth block.

The initial training data of the simultaneous condition for participants A and B are absent for block one to six and one to nine, respectively. These two participants started the experiment with a programming error that entailed that the presentation of the visual and the auditory stimuli in the simultaneous condition were not permanently isochronous. The sequential condition was not affected by the error. They trained up to their ninth and sixth block, respectively and discontinued practicing. Due to the fact that they had nonetheless some kind of practice experience in the simultaneous condition although not with a stable simultaneous presentation of the two tasks, they were re-invited after about one month. They completed their training schedule up to the 15th training block with the correct stimulus timing in the simultaneous condition and the same amount of sequential trials.

The first five trials in each session were training trials and were excluded from further analysis as well as RTs of trials with a wrong answer in either task. RTs that were smaller than 200 ms were regarded as anticipations and were therefore discarded. RTs that surpassed the individuals' mean of each session and condition by three standard deviations (*SD*) were excluded as outliers. For each updating sequence of the sequential condition, the updating RT for the first operation was eliminated because it was associated with a switch from one task to the other. The remaining RTs were aggregated within trials. In the sequential condition this was separately done for the numerical and the spatial task. In the simultaneous condition, there was only one RT for one pair of a numerical and a spatial updating. The alpha level for all statistical tests of the present and the following experiments was set to .05.

Sequential RTs. Figures 2.3 to 2.5 show the mean updating RTs of both tasks in the sequential condition separately for each participant over the training blocks.

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[1] The subject ids A to J code the ranking of the residual dual-task costs reached by each subject in an ascending order. They do not correspond to the subject ids randomly assigned prior to the training course.

Dual-task costs. Dual-task costs were defined as the difference between the observed RT in the simultaneous condition and the maximum sequential RTs (max(seq) RT) of the same training block based on the rationale of the model for parallel processing discussed above. In order to receive the maximum sequential RTs the following algorithm was applied. The updating RTs of the numerical and the spatial tasks within each trial of the sequential condition were paired, starting with the second. Accordingly, the second numerical updating RT was compared to the second spatial updating RT of the same trial and the longer was chosen. Likewise, the third numerical was compared with the third spatial updating RT and the longer RT was chosen, and so on. This yielded a series of the maximum sequential updating RTs. The maximum sequential updating RTs of one sequence were averaged for each trial. These max(seq) RTs were compared with the mean RTs of the simultaneous condition.

Figures 2.6 to 2.8 show the mean RTs of the simultaneous condition and the max(seq) RTs as predictions of parallel processing. Accordingly, the mean percent errors (PE) of the simultaneous and the sequential condition for each training block are shown. The order of participants in Figures 2.6 to 2.8 mirrors the ranking of their residual dual-task costs in an ascending order.

For each participant it was tested whether there was a significant difference between the RTs of the simultaneous updating and the prediction of parallel processing. T tests were conduced separately for each participant and training block. Statistically indistinguishable RTs were interpreted as vanished dual-task costs in RTs. Dual-task costs in errors were examined via conducting chi-square tests for the number of errors in the simultaneous vs. the sequential condition for each participant and training block. The RT and PE data both entered in the participant's classification of serial vs. parallel processors after the following criterion, which was adopted by Göthe et al. (Göthe, Oberauer, & Kliegl, 2007).

The last three training phases of each participant were considered. For these it was determined whether the RTs of the simultaneous condition reached the prediction of parallel processing given by the max(seq) RTs without any speed-accuracy trade-off. In doing so three categories were possible: success, failure, and ambiguous. Ambiguous were either training blocks where (A) the RT criterion was met but the errors of the simultaneous condition were significantly higher than for the sequential condition; or (B) the RT criterion was not met but there were significantly more errors in the sequential than in the simultaneous condition. To identify participants with parallel processing I excluded ambiguous performance blocks and counted the last three training blocks that were either successes or failures. If two of the three were successes, we decided for parallel processing otherwise for sequential processing. Table 2.1 displays the mean RTs, PEs and the test statistics for the last three training blocks of each participant. Table 2.2 summarizes the classification of parallel vs. serial processors.

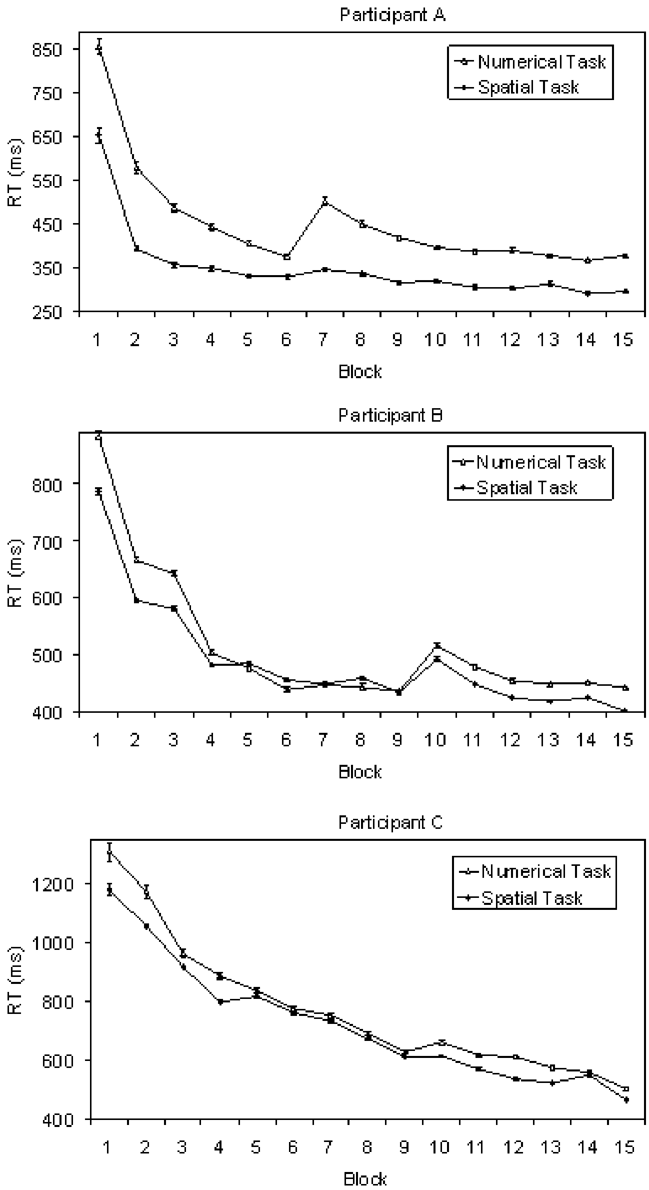

Figure 2.3. Mean RTs of numerical and spatial updating in the sequential condition as a function of training block for Participants A to C. Error bars represent standard errors of the mean. Note the different RT ranges (left y-axis) across participants due to plotting individual training trajectories.

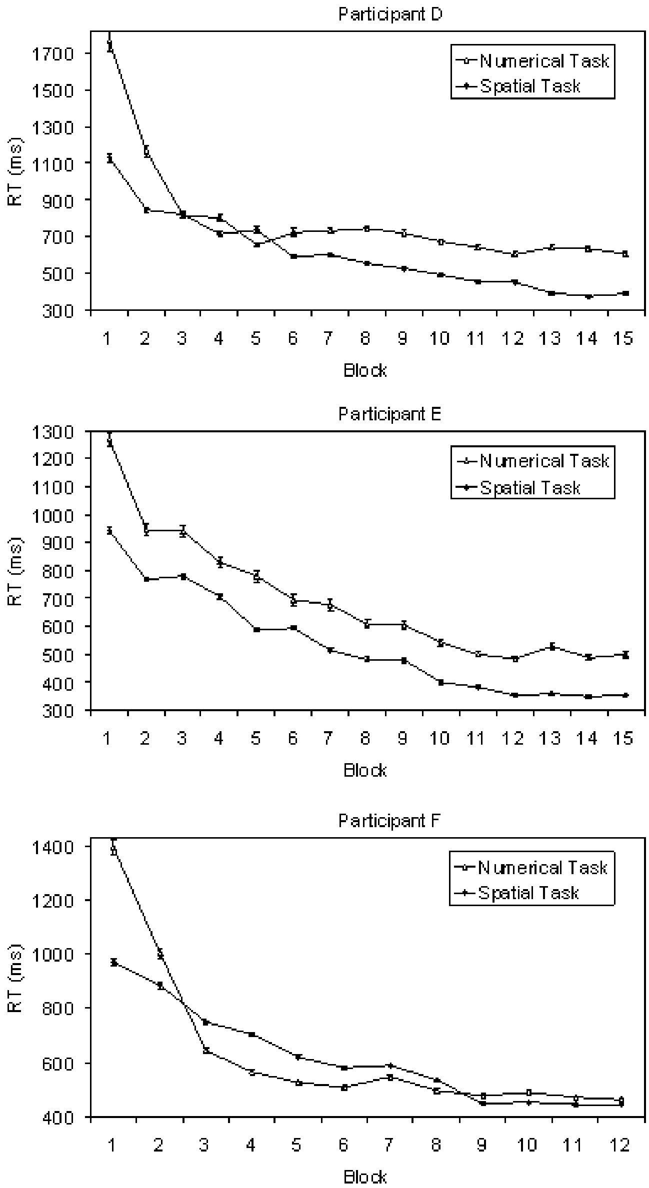

Figure 2.4. Mean RTs of numerical and spatial updating in the sequential condition as a function of training block for Participants D to F. Error bars represent standard errors of the mean. Note the different RT ranges across participants due to plotting individual training trajectories.

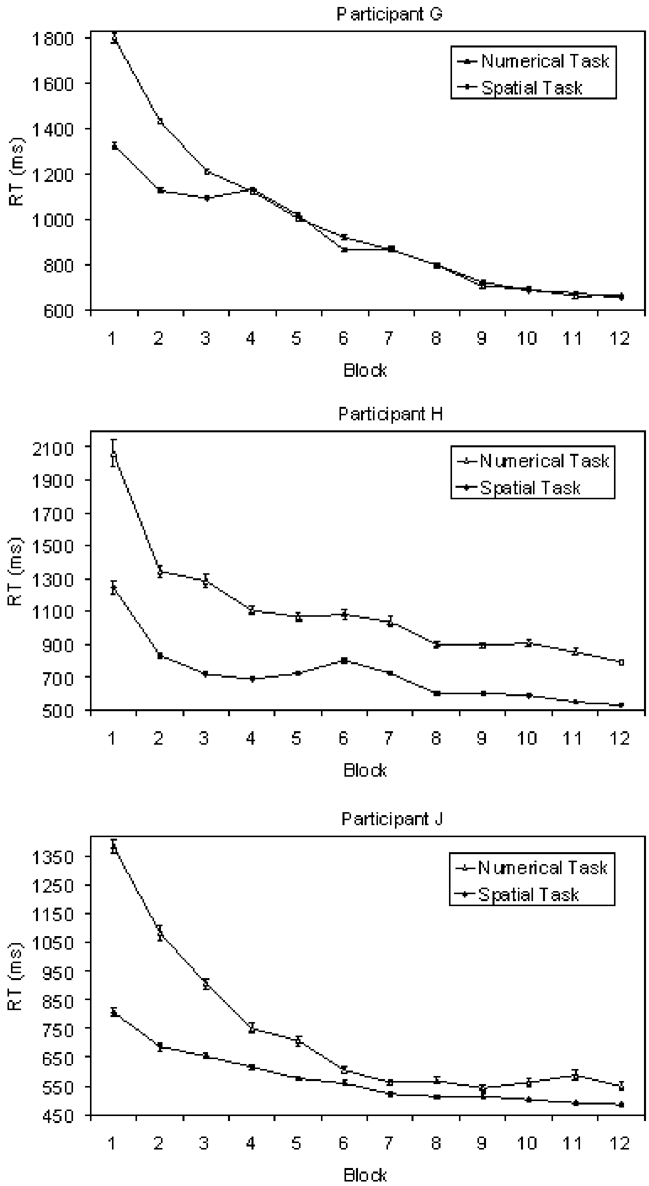

Figure 2.5. Mean RTs of numerical and spatial updating in the sequential condition as a function of training block for Participants G to J. Error bars represent standard errors of the mean. Note the different RT ranges across participants due to plotting individual training trajectories.

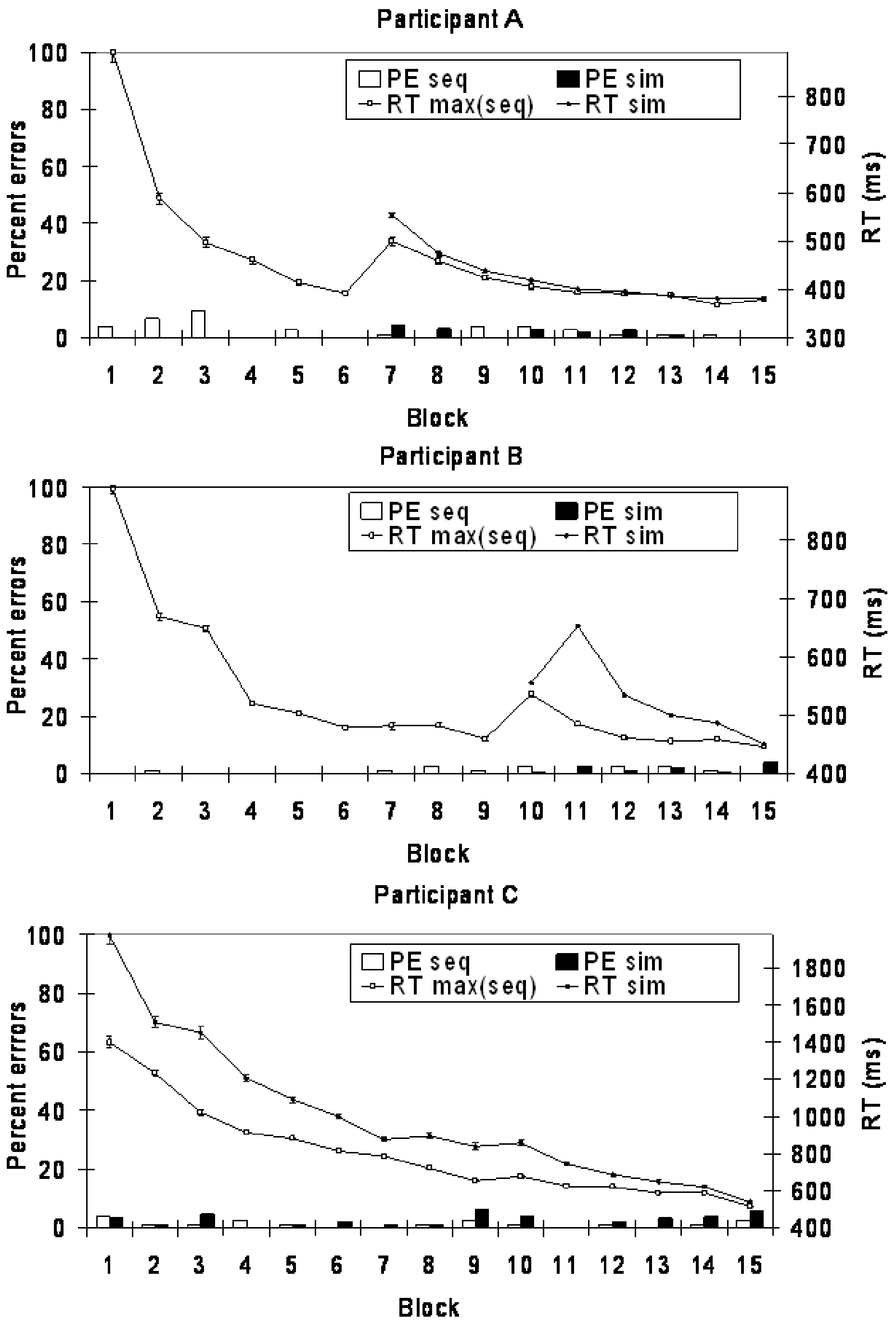

Figure 2.6. Training data of Participant A, B and C who trained for a whole of 15 training blocks. Mean RTs (left y-axis) for the simultaneous condition (RT sim) and the maximum sequential RTs (RT max(seq)) are given by training block. Error bars represent standard errors of the mean. Percentages of errors (right y-axis) for each training block are averaged over task (numerical, spatial) for the simultaneous (PE sim) and the sequential condition (PE seq). Note the different RT ranges (left y-axis) across participants due to plotting individual training trajectories.

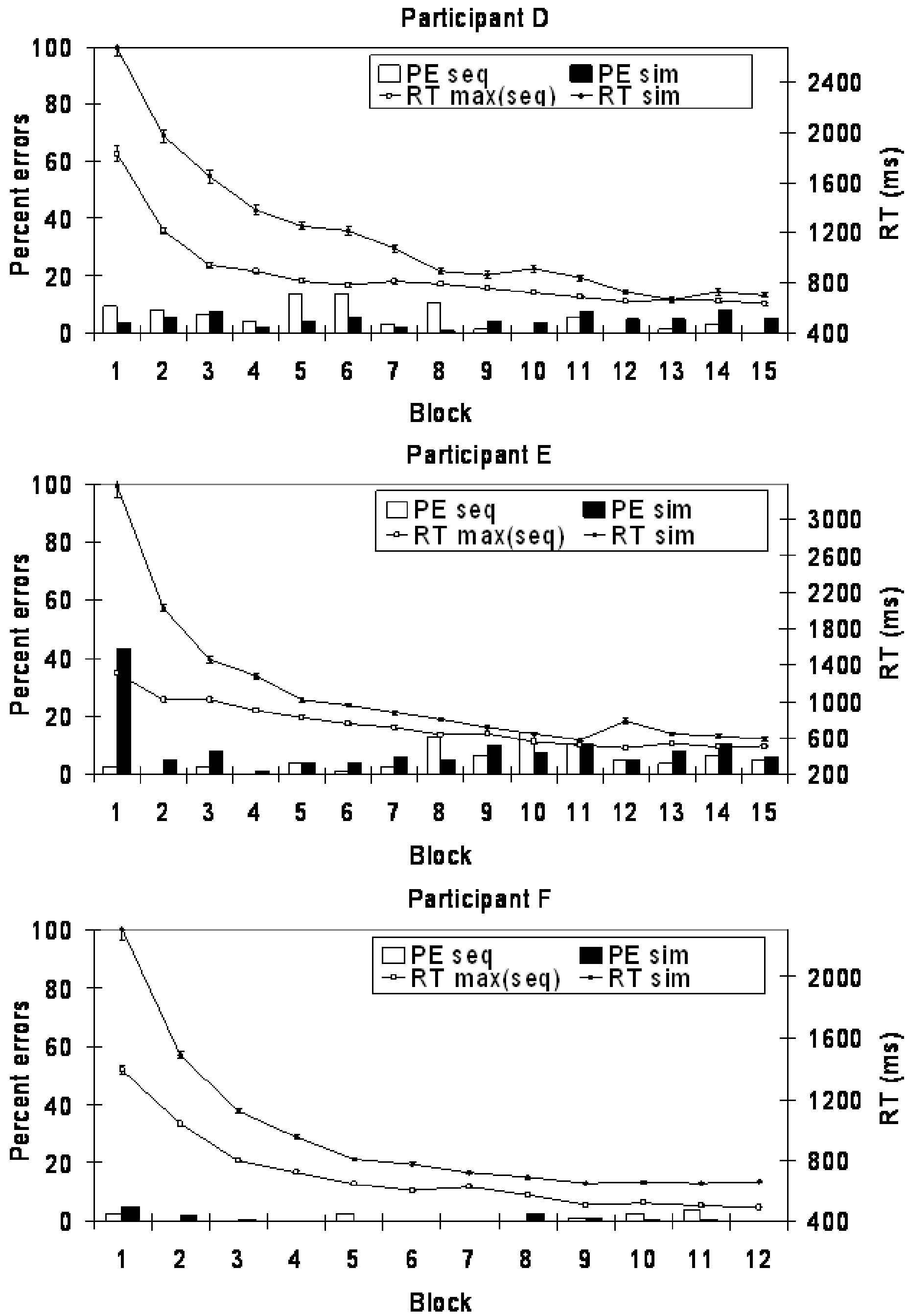

Figure 2.7. Training data of Participant D, E and F who trained for a whole of 15, 15 and twelve training blocks, respectively. Mean RTs (left y-axis) for the simultaneous condition (RT sim) and the maximum sequential RTs (RT max(seq)),are given by training block. Error bars represent standard errors of the mean. Percentages of errors (right y-axis) for each training block are averaged over task (numerical, spatial) and for the simultaneous (PE sim) and the sequential condition (PE seq). Note the different RT ranges (left y-axis) across participants due to plotting individual training trajectories.

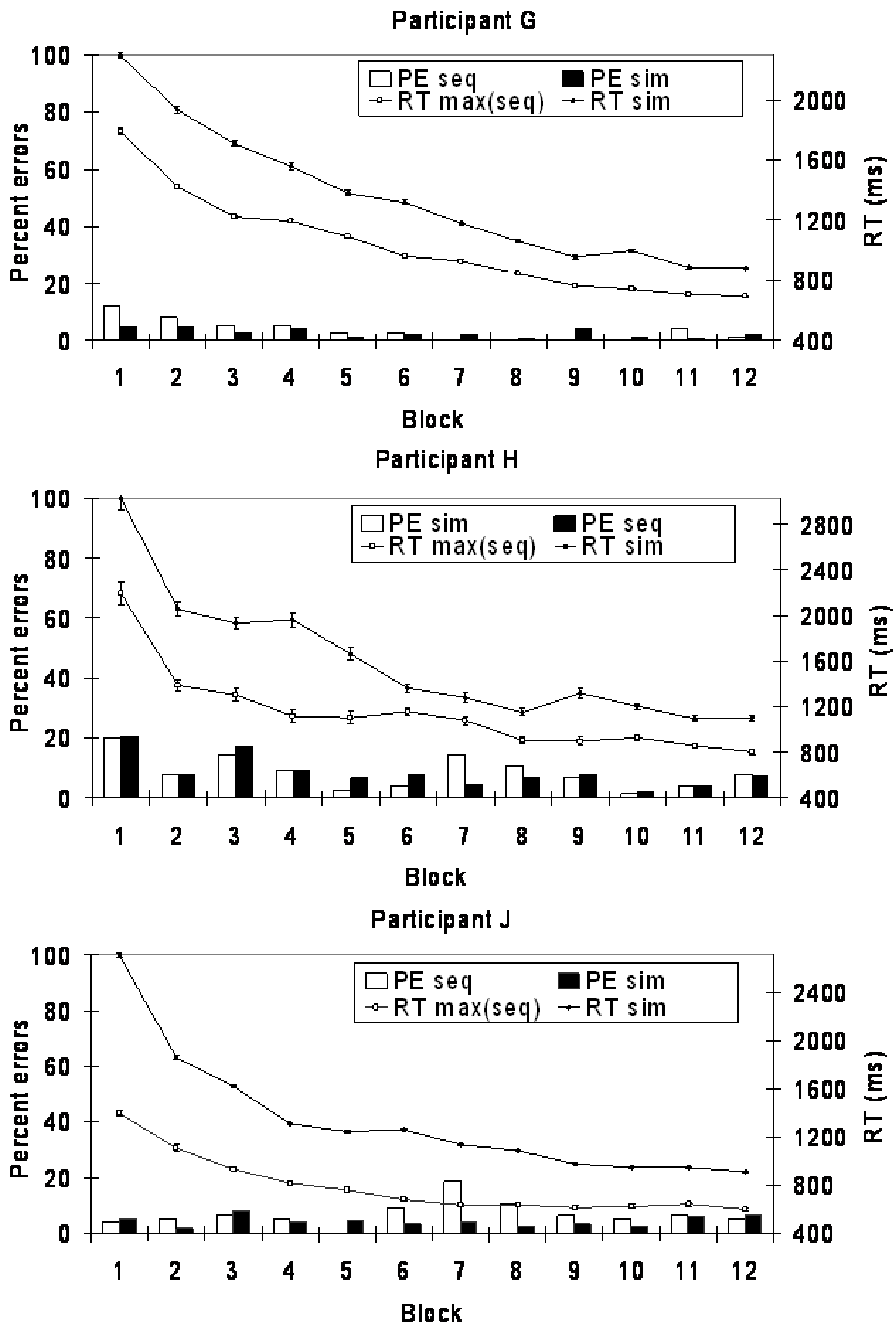

Figure 2.8. Training data of Participant G, H and J, who trained for a whole of twelve training blocks. Mean RTs (left y-axis) for the simultaneous condition (RT sim) and the maximum sequential RTs (RT max(seq)) are given by training block. Error bars represent standard errors of the mean. Percentages of errors (right y-axis) for each training block are averaged over task (numerical, spatial) for the simultaneous (PE sim) and the sequential condition (PE seq). Note the different RT ranges (left y-axis) across participants due to plotting individual training trajectories.

Table 2.1. Mean RTs, PEs and test statistics for the last three training blocks of each participant. *SD*s are given in brackets for the RTs and the PEs.

ID	Block	RT			PE		
		Max (seq)	Sim	*T*(df)/	Seq	Sim	χ^2
A	13	388 (37)	387 (37)	.24 (145)	1.33 (11.55)	1.33 (8.11)	3.01
	14	369 (25)	382 (28)	-2.96 (147)*	1.33 (11.55)	0	1.01
	15	379 (35)	382 (29)	-.42 (147)	0	0	-
B	13	455 (14)	500 (55)	-6.65 (81.98)*	2.67 (16.22)	2.00 (12.84)	1.33
	14	459 (22)	486 (45)	-4.71 (105)*	1.33 (11.55)	.67 (5.77)	2.00
	15	446 (12)	450 (26)	-1.29 (97.02)	0	4.00 (17.93)	4.11
C	13	588 (46)	652 (46)	-8.38 (144)*	0	3.33 (15.01)	4.11
	14	591 (38)	622 (65)	-3.48 (111.20)*	1.33 (11.55)	4.00 (15.94)	4.11
	15	518 (35)	541 (48)	-3.21 (119.85)*	2.67 (16.22)	6.00 (18.31)	7.59*
D	13	664 (138)	659 (164)	.22 (138)	1.33 (11.54)	4.67 (18.70)	3.44
	14	657 (113)	727 (223)	-2.29 (92.07)*	2.67 (16.22)	8.00 (21.81)	8.46*
	15	631 (109)	699 (157)	-3.00 (122.53)*	0	4.67 (18.70)	5.17
E	13	541 (116)	646 (171)	-4.17 (113.43)*	4.00 (19.73)	8.00 (23.31)	6.26*
	14	500 (80)	620 (137)	-6.05 (96.02)*	6.67 (25.11)	10.67 (25.06)	10.99*
	15	513 (92)	591 (148)	-3.66 (109.94)*	5.33 (22.62)	6.00 (18.31)	8.92*
F	10	522 (46)	658 (69)	-14.08 (126.96)*	2.67 (16.22)	.67 (5.77)	3.01
	11	506 (42)	652 (63)	-16.36 (127.17)*	4.00 (19.73)	.67 (5.77)	4.03
	12	494 (34)	660 (54)	-22.57 (124.51)*	0	0	-
G	10	742 (55)	996 (86)	-21.24 (121.83)*	0	1.33 (8.11)	2.03
	11	710 (44)	887 (72)	-17.95 (121.37)*	4.00 (19.73)	.67 (5.77)	4.03
	12	694 (36)	883 (57)	-23.77 (118.32)*	1.33 (11.55)	2.00 (9.86)	4.03
H	10	929 (72)	1203 (200)	-9.22 (132.66)*	1.33 (11.55)	2.00 (9.86)	4.03
	11	860 (150)	1096 (194)	-8.01 (137)*	4.00 (19.73)	4.00 (15.94)	5.03
	12	807 (117)	1103 (209)	-10.14 (103.57)*	8.00 (27.31)	7.33 (22.80)	6.03*
J	10	628 (94)	949 (94)	-11.34 (95.78)*	5.33 (22.62)	2.67 (11.31)	8.00*
	11	644 (102)	949 (208)	-10.85 (98.11)*	6.67 (25.11)	6.00 (20.07)	6.32*
	12	602 (45)	914 (154)	-14.98 (100.37)*	5.33 (22.62)	6.67 (23.73)	2.03

Note: Mean RTs are in milliseconds. In the sequential condition, max(seq) RTs are given. Test statistics are *T* values) for RTs with degrees of freedom (df) in brackets. Noninteger dfs result due to a correction according to the violation of the equality of variances tested by the Levene's test. Test statistics are $\chi 2$ values for PEs. Test statistics are marked with an asterix if t-tests or $\chi 2$-tests approach a significance level of $p < 0.05$.

Table 2.2. Classification of participants as parallel or serial processors.

ID	Block						Parallel processor
	Last-2		Last-1		Last		
	Dual-task costs in RT	Signif. more errors	Dual-task costs in RT	Signif. more errors	Dual-task costs in RT	Signif. more errors	
A	-	-	+	-	-	-	+
B	+	-	+	-	-	-	-
C	+	-	+	-	+	sim	-
D	-	-	+	sim	+	-	-
E	+	sim	+	sim	+	sim	-
F	+	-	+	-	+	-	-
G	+	-	+	-	+	-	-
H	+	-	+	-	+	seq	-
J	+	seq	+	seq	+	-	-

Note. A dash represents no significant differences between the sequential and simultaneous conditions for the PE data or the max(seq) and simultaneous conditions for the RT data. A plus sign represents significantly longer RTs in the simultaneous condition than max(seq), reflecting dual-task costs. Significant differences in PEs were observed in both directions: seq means that more errors were made in the sequential condition, whereas sim reflects more errors in the simultaneous condition. In the Parallel processor column, a plus sign means that the participant was classified as a parallel processor, and a dash signifies that he or she was classified as a serial processor.

According to this criterion, Participant A was the only parallel processor observed in this experiment. As can be seen in Figure 2.6, this participant showed parallel processing for two of the last three sessions. She restarted practicing at the seventh block and only needed one block to reach the criterion of parallel processing. After the seventh block she constantly showed vanished dual-task costs in RTs and PEs except for the 14th block, where small costs in RTs of about 13 ms became significant. Participant B and D showed vanished dual-task costs in RTs and PEs at least for one of the last three training blocks. For most of the participants costs did not vanish at all for one of their last three training blocks.

Some participants practiced more than others. However, strong inter-individual differences were even visible for keeping practice amount equal. The dual-task costs of the twelfth practice block were chosen to compare the dual-task costs of the participants, because this was the last training block that was realized for all participants. Table 2.3 shows the residual dual-task costs of all nine participants for the twelfth training block. There were two broad clusters of dual-task cost values. As can be seen Participant A to D together yielded mean dual-task costs of 56.29 ms (*SD*: 35.78) whereas Participant F to J yielded higher mean dual-task costs of 240.59 ms (*SD*: 73.84). The participants with the dual-task costs below 100 ms (A to D) at their twelfth block were the participants that received three more blocks practice and thus had the opportunity to further reduce dual-task costs. This was especially gainful for Participants B and C. Participant A had already vanished costs in RTs at block twelve. Participant D only could reduce costs for about 15 ms within these additional three blocks.

Participant E showed a discontinuous data curve. Despite a continuous training schedule without time breaks of more than 1 week the dual-task costs of this participant increased from the eleventh to the twelfth practice block from 54.68 ms to 292.97 ms, respectively. Looking at the practice data of Participant E in Figure 2.7 it becomes obvious that this participant had already constantly undershot the dual-task costs of about 293 ms at the twelfth block since the fifth through the eleventh training block. With further practice this participant once again was able to reduced costs to a value of 77.97 ms at the 15th block. The re-emergence in dual-task costs for the twelfth block was interpreted as a random shift in the task overlapping strategy of Participant E, which gives a hint to the fact that the ability to timeshare two processing streams, once yielded, might not be a stable ability.

Table 2.3. Mean dual-task costs in RTs for the twelfth and the 15th training block of each participant.

ID	dual-task costs (ms) twelfth block	dual-task costs (ms) 15th block
A	3.33	2.22
B	72.84	4.40
C	67.45	23.07
D	81.52	67.89
E	292.97	77.97
F	166.08	-
G	188.63	-
H	269.43	-
J	311.21	-

Since the Participants F- J did not get further practice opportunity, it is possible that they could have gained from further practice and thus could have achieved an equal low dual-task cost level as Participants A- F. To examine this possibility power functions were fitted to the dual-task costs of each participant through Block one to twelve. The individual functions were extrapolated using the best fitting parameters to obtain the number of blocks needed for each participant of the high interference group to achieve dual-task costs equivalent to the average dual-task cost of the low interference participants (A- E) at Block 15 (i.e., 48 ms). According to this extrapolation, the high interference participants would have needed an average of 398 training blocks to reach the level of dual-task performance that the low interference participants reached after 15 blocks. This furthermore suggests that the possibility that these participants would ever process the two tasks in parallel is very low.

2.3. Discussion

The purpose of Experiment 1 was to investigate whether two cognitive tasks can be processed simultaneously when both contain an arbitrary S-R mapping. The results showed that eight participants were not able to reach the criterion of parallel processing at the end of practice. Only one participant was able to show parallel processing (Participant A). Therefore, it could be demonstrated, that parallel processing of two tasks containing both arbitrary S-R mappings is generally possible. Nevertheless, the majority of participants did not accomplish parallel processing.

Comparison to earlier studies

In the following I compare the present results to the earlier findings of Oberauer and Kliegl (2004) and Göthe, Oberauer and Kliegl (2007) in order to determine whether the parallel processing ability is reduced for two tasks containing arbitrary S-R mappings. In these studies the young subgroup of participants has trained the same verbal memory-updating task as the participants of the present experiment. Only the spatial task differed between the present experiment and the two earlier studies with respect to the S-R mapping. The S-R mapping was arbitrary for the present and compatible for the earlier studies. For the comparison multiple indicators are considered: the ratio of parallel to serial processors at the end of practice, the mean residual dual-task costs across participants, the mean practice opportunity measured in dual-task trials, and the single-task performance.

At first I consider the ratio of parallel to serial processors observed at the end of practice. In all studies the same classification scheme is used to decide for parallel or serial processors. While in the two earlier studies (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) nine young participants showed parallel and three serial processing, in the present study only one participant showed parallel but eight serial processing. This shows that the dominating result in the present study was serial but parallel processing in the earlier studies. Expressed in dual-task cost, that were computed identically for all the respective studies (as described in the Result section of Experiment 1), the young participants of Oberauer and Kliegl and Göthe et al. yielded 19 ms costs on average (*SD*: 36 ms) at the end of practice. The participants of the present study resulted in 126 ms (*SD*: 120 ms) dual-task costs at the end of practice. This difference in dual-task costs is significant, $t(9.076)= 2.59$, $p= .029$ indicating a reduced parallel processing potential of the two tasks in the present compared to the earlier studies.

The present and the two comparison studies differ in the maximal practice opportunity that was provided. Nevertheless this can not explain the higher costs in the present experiment, since practice opportunity measured in mean dual-task trials was higher for the present compared to the earlier studies. In the present experiment the participants received on average 1093 trials dual-task practice. The participants of the comparison studies received only 720 trials dual-task practice. That means although practice opportunity in the present context was higher compared to the former studies the dual-task costs were still significantly higher.

However, the found direction of the dual-task costs difference would be predicted by the central bottleneck account if the single-task RTs in the present study were also higher compared to Oberauer and Kliegl (2004) and Göthe et al. (Göthe, Oberauer, & Kliegl, 2007). The bottleneck account assumes dual-task costs to be determined by central processing duration of the task that is processed first. Hence, an observation of higher single-task RTs in the present study would flaw supervision-based crosstalk as an explanation for the reduced parallel processing ability of two tasks containing an arbitrary S-R mapping. But comparing the RTs of the numerical and the spatial task out of the sequential updating condition between the two studies no significant difference is observable. At the end of practice the participants processed the (identical) numerical task in 544 ms (*SD*:128 ms) and in 490 ms (*SD*: 70 ms), for the present and the comparison studies respectively. This difference was not significant, $t(19)= 1.25$, $p=.226$. The RTs for the spatial task also did not significantly differ between the present ($M= 446$ ms, $SD= 106$ ms) and the comparison studies ($M= 430$ ms, $SD= 71$ ms), $t(19)= .43$, $p=.671$. This was the case even though the tasks differed in the S-R mappings. Hence, there is no evidence for higher single-task RTs in the present compared to Oberauer and Kliegl and Göthe et al. study that could have caused the observed dual-task cost difference at the end of practice according to the central bottleneck account. Taken together it has to be concluded that the particular task characteristic implemented in the present experiment, i.e. two tasks with arbitrary S-R mappings have resulted in higher dual-task costs compared to the situation in Oberauer and Kliegl and Göthe et al. where at least one task contains a compatible S-R mapping. This difference in costs cannot be attributed to lesser practice opportunity or higher single-task RTs.

Supervision-based crosstalk

As the supervision-based crosstalk account predicted I found evidence that the ability to process the two tasks in parallel is reduced when both tasks are under top-down control compared to a situation where only one task is. Applying two non compatible S-R mappings at the same time might create a situation where the control signals supervising their implementation can be misled. Hence, errors can arise due to the wrong application of control signals of one task to the other task. Processing the tasks serially can avoid crosstalk of control signals and subsequent errors. As such, the shift from serial to parallel processing with practice is less supported if both tasks contain S-R mappings that are under strong top-down control compared to the situation where only one task is mediated by executive control signals. Admittedly, this conclusion is based on a comparison between experiments. Therefore, in Experiment 2 I tested two dual-task groups differing in the S-R mapping of one task within one experiment. To anticipate, the results of Experiment 2 unequivocally support the present findings of the between experiment comparison.

Hence, this comparison shows that conditions for parallel processing were not favourable for the two non compatible tasks of the present experiment. Nevertheless, Participant A showed parallel processing of the two tasks with practice. Participant A shows a very fast realization of parallel processing of the two tasks after the re-invitation (after only one additional training block). Therefore, the data pattern of Participant A strongly differs from the rest of the tested participants. Speculating on that it could be interpreted as a more or less general strategy of Participant A to process the two tasks in parallel. However, the participant did not explicitly reported that. Of course, it can’t be ruled out that with additional practice other participants have given up the serial scheduling scheme for the two tasks. Especially the training data of Participants B and D seemed very promising, as they already met the criterion of parallel processing for one single training block. Taken together participants with low dual-task interference (B to E) yielded on average 48 ms dual-task costs at the end of practice. The other participants (F to J) were not able to further reduce costs to a value lower than 240 ms on average. Moreover, the extrapolation of the training data of these latter participants revealed that they would have needed on average 398 further training blocks to achieve dual-task costs equivalent to the average dual-task cost that was reached by the participants of the low interference group (i.e. 48 ms) after 15 training blocks. Therefore, I believe that moderately more practice for the participants of the high interference would not have changed the results qualitatively concerning their parallel processing ability. This result suggests that participants differ in how to accommodate to task dependent conditions (Meyer et al., 1995).

Nevertheless, how can parallel processing be accomplished facing supervision-based crosstalk? Practice is known to reduce the influence of top-down control signals for non-compatible mappings and can lead to the establishment of direct S-R associations. Subsequently, these are automatically activated without the mediation of top-down control parameters. Proctor and Lu (Proctor & Lu, 1999), for example, could show this for incompatible S-R mappings. Their subjects practiced a spatial compatibility task for three sessions with either a compatible (left stimulus → left response key, right stimulus → right response key) or an incompatible (right stimulus → left response key, left stimulus → right response key) before they performed a Standard Simon task. In the Simon task participants are required to respond e.g. to the colour of a stimulus with a left-right response, i.e. to press the left button when the stimulus is green and to press the right button when the stimulus is red, thereby ignoring the location of the stimulus that also either can be left or right. On congruent trials the location of the stimulus corresponds to the response location (a green stimulus appearing on the left side→ left response key or a red stimulus appearing on the right side→ right response key). On incongruent trials the location of the stimulus does not correspond to the response location (a red stimulus appearing on the left side→ right response key or a green stimulus appearing on the right side→ left response key). The typical observation in the Simon task is that reactions are usually faster and more accurate for congruent then for incongruent trials, even if the stimulus location is irrelevant to the task (for a review seeSimon, 1990). This is referred to as the Simon effect. In the experiment of Proctor and Vu a Simon effect of normal size was obtained after a practice with compatible mapping, but an inverted effect was observed after incompatible mapping practice. This means that in the incompatible practice group the RTs for the incompatible trials in the Simon task were faster than for the compatible trials. The authors assumed that learning an incompatible mapping leads to the formation of direct S-R associations that are then automatically activated in the Simon task, too, thus cancel out, and even overwrite the usual benefits of spatial correspondence.

To the degree that the implementation of S-R mappings becomes autonomous of control signals the potential of supervision-based crosstalk and therefore the error potential is decreased. Hence, with practice the implementation of two non compatible S-R mappings could be realized without the potential of confusion of their control signals. However, this process takes longer for non compatible S-R mapping tasks than for compatible. Nevertheless, once acquired, direct S-R associations support the shift from serial to parallel processing as could be observed for Participant A.

Automatization and latent bottleneck

The establishment of direct S-R associations does, however, not mean that the tasks per se are automized and do not require central processing. This automatization hypothesis is one of two possible alternative explanations for the vanished dual-task costs of Participant A that try to challenge the interpretation of parallel processing by assuming a bypass of the bottleneck under certain conditions. For these two scenarios the bottleneck account predicts zero dual-task costs. As mentioned, one hypothesis is to postulate that one or both tasks are automized. Hence, there is no real parallel processing of the central processing stages of the two tasks, as there is (are) no central stage(s). On the other hand the bottleneck could become latent (Ruthruff et al., 2003). The latent bottleneck refers to a situation in which the pre-bottleneck stage of one task is at least as long as the pre- plus bottleneck stage of the other task, so that the two tasks never compete for the bottleneck. A latent bottleneck is more likely when the two bottleneck stages are rather short, which minimizes the probability of their temporal overlap. Shortening of central bottleneck stages results from practice (Ruthruff, Johnston, & Van Selst, 2001). Each scenario - the automatization and the latent bottleneck scenario - assumes that practice on the individual tasks reduces the time each of them demands the bottleneck. The automatization account thereby assumes that at least for one task central processing, i.e. the bottleneck stage is completely vanished. The latent bottleneck account assumes that the bottleneck stage is reduced to a very short period. Importantly, both scenarios predict that practicing the tasks separately is sufficient for the shortening of the bottleneck stage and hence for the reduction of dual-task costs. To test this prediction, Oberauer & Kliegl (2004, Experiment 2) practiced one group of participants on the dual-task combination of numerical and spatial updating, and another group on single-task conditions of these tasks for the same overall amount of practice. Only the group practicing the dual-task condition showed substantially diminished dual-task costs. This finding rules out the automatization and the latent bottleneck account also for the present results of vanished dual-task costs for Participant A. Thus, postulating a parallel processing schedule for Participant A applies to the data best.

Conclusion

To summarize, it could be shown that parallel processing with a numerical and a spatial task - both containing arbitrary S-R mappings - is possible although the strategy to process them serially was maintained by the majority of participants. Comparing the result to Oberauer and Kliegl and Göthe et al., it has to be concluded that tasks with low S-R compatibility have a reduced potential to be processed in parallel, particularly in comparison to a task combination where at least one task contains a compatible S-R mapping. This is attributed to the higher and long enduring top-down control demand of non compatible S-R mapping tasks. In dual-task situations this leads to higher potential of crosstalk between control signals of two tasks which can be avoided by processing the tasks serially. This serial processing prevents crosstalk-associated errors at the cost of total processing time. The supervision- based crosstalk for two tasks containing arbitrary S-R mappings hence could have influenced the results of Brambosch not yielding parallel processing for any participant after practice even after the spatial recoding of the letter task. The support for the present interpretation, however bases on a between experiment comparison. Therefore, the next experiment directly compares the dual-task costs of two groups working on the same two tasks, differing only in the S-R mapping of one task.

3. Experiment 2 – Two tasks with non-compatible S-R mapping vs. two tasks with one task containing a compatible S-R mapping

Experiment 1 demonstrated parallel processing of two tasks containing both arbitrary S-R mappings. But only one out of nine participants was able to process the two tasks in parallel, much less participants than in conditions, where at least one task contained a compatible S-R mapping (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004). One potential problem with arbitrary S-R mappings is enhanced crosstalk between top-down control signals supervising S-R mapping of both tasks (Hommel, 1997; Kornblum, Hasbroucq, & Osman, 1990). Hence it is likely, that most participants of Experiment 1 scheduled the two tasks serially to prevent crosstalk.

However, the comparison of Experiment 1 and the previous studies (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) represents only a between experiment comparison. Experiment 2 directly examines whether the compatibility of S-R mappings for the two tasks affects the dual-task performance. Dual-task costs of two different groups is compared: one group working on two tasks both containing non-compatible S-R mappings and one group working on two tasks where at least one tasks contained a compatible and the other a non-compatible S-R mapping. The question was whether after the same amount of practice the dual-task costs across groups were identical or whether they were increased for the group with two non-compatible S-R mapping tasks.

The present study

Both dual-task groups in Experiment 2 practiced the same two memory updating tasks- a verbal-numerical and a spatial task. Crucially, the S-R mapping of the spatial task differed between the two groups being compatible for one group and incompatible for the other group. The verbal task contained an arbitrary S-R mapping for both groups and was the same as in the Experiment 1. The task was to carry out simple calculations, i.e. adding two or subtracting one within the range of the numbers from one to nine according to the presentations of two possible tones. Compared to Experiment 1 the spatial task had minor changes in the visual display and in S-R mapping. Again, the task was to mentally shift the position of a dot. The dot had to be shifted within a ring divided into eight sections (see Figure 3.1). The updating stimuli, i.e. the stimuli indicating the direction of the shift were arrows pointing into one of two possible directions: a single and a double arrow (two parallel plotted arrows) pointing counter clockwise and clockwise, respectively.

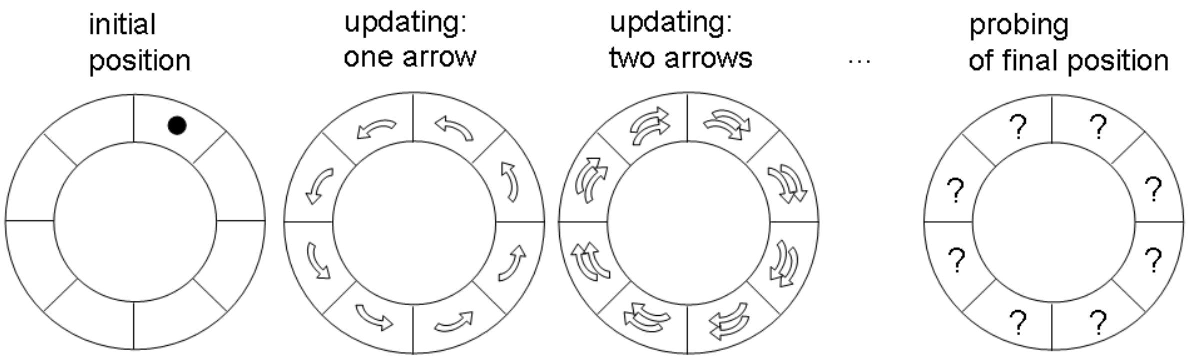

Figure 3.1. Example of the spatial updating task used in Experiment 2. The initial dot position was presented within a ring that was divided into eight sections. The updating stimuli comprised of two possible arrows: a single arrow pointing counter clockwise or a double arrow pointing clockwise. For the compatible S-R mapping group the dot had to be shifted into the indicated direction at the indicated distance. For the incompatible mapping group the single arrow demanded a double shift against the indicated direction and the double arrow demanded a single shift against the indicated direction. The example only shows two out of seven to eight possible updating cycles. For the probing of the final position question marks appeared in each possible location within the ring.

For the compatible S-R mapping group the single arrow indicated to shift the dot one section into the counter clockwise direction. Analogous, the double arrow denoted to shift the dot position two sections into the clockwise direction. For the incompatible S-R mapping group the distance and the direction that was displayed by the arrow/ arrows had to be reversed. Hence, a single arrow demanded a two step shifting into the opposite direction to what was indicated by the arrow (i.e. a double clockwise shift was indicated by a counter-clockwise pointing arrow) and a double arrow a one step shifting into the opposite direction (i.e. a single counter clockwise shift was indicated by a double clockwise pointing arrow). Using the simple reverse rule for the incompatible S-R mapping group, should maximize the chance that performance for the incompatible compared to the compatible group did not strongly differ in RT and PE levels. Hence, potential differences in dual-task costs could not be attributed to differences in difficulty per se but to differences due to the S-R mappings, i.e. differences in executive control demands. This should produce low supervision-based crosstalk for the compatible mapping group and high supervision-based crosstalk for the incompatible mapping group. Crosstalk between executive control signals for the incompatible group should increase dual-task costs compared to the compatible group. This difference should be higher than potential differences in single-task performance between the two groups.

3.1. Method

Participants. The participants were 22 psychology undergraduates of the University Potsdam with a mean age of 21 years (range 19- 24 years). They received course credit or six Euro for each 30-45-min session.

Design and Procedure. Two memory updating tasks were implemented in Experiment 2- a verbal and a spatial. The verbal task was the same as in Experiment 1. The memory-updating tasks had the same procedural order of events as in Experiment 1: presentation of starting values, updating and probing of final values. For the spatial task a dot appeared in one of the eight possible sections within a ring (see Figure 3.1). There were two possible updating stimuli for the spatial task: one single arrow pointing counterclockwise or two parallel plotted arrows (a double arrow) pointing clockwise. The arrow(s) appeared in each of the eight possible sections of the ring. This should made sure that no spatial attention shift towards a, for example, centrally presented updating arrow had to be done interfering with the actual position. Probing the final position the German word for dot ("Punkt?") appeared in the middle of the screen. The participants had to click with the computer mouse into one of the eight possible locations within the ring to indicate the final position of the dot. For the numerical task the initial digit was presented in each of the eight sections of the ring. See Figure 3.2 for a schematic structure of one trial of the simultaneous updating condition.

The experimental design was the same as in Experiment 1 except minor changes. The whole experiment consisted of twelve training sessions for each participant. Within one session there were four blocks, two for each updating condition (simultaneous or sequential). One block included 20 trials. At the beginning of each block the updating condition was shown. The updating conditions alternated between blocks. The order of the updating conditions was counterbalanced across subjects. The first session started with the presentation of two practice blocks, one for each updating condition comprising of two practice trials each.

The two S-R mapping groups differed in the instruction with respect to the S-R mapping of the spatial task. In the compatible S-R mapping group the distance and the direction of the shifting was indicated by the arrow itself. A single arrow meant to shift the dot one section and a double arrow indicated to shift the dot position two sections in the indicated direction. For the incompatible S-R mapping group the information about distance and direction of the arrow/arrows had to be reversed. A single counter-clockwise pointing arrow had to be translated into a double clockwise shift, respectively a double clockwise pointing arrow into a single counter-clockwise shift of the dot position. Feedback was given at the end of each trial.

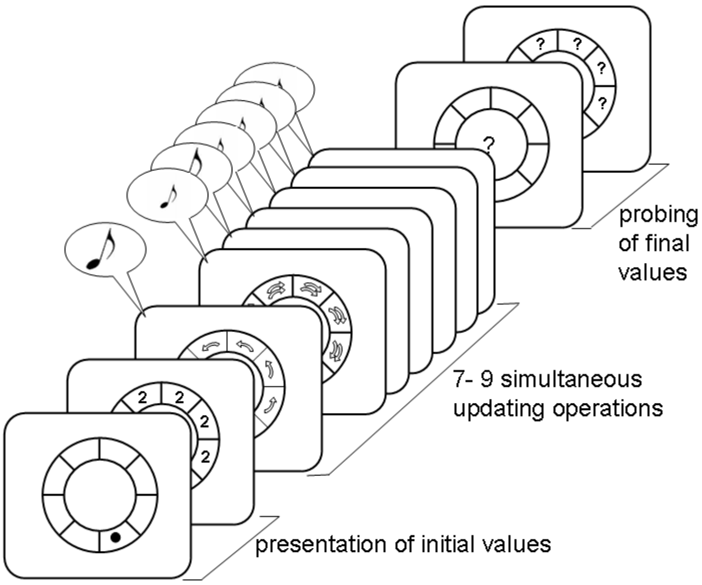

Figure 3.2. Phases in the memory-updating paradigm with the spatial and verbal task used in Experiment 2. The example shows the simultaneous updating condition.

3.2. Results

Practice trials and trials with wrong answers were excluded from the analysis. In addition, RTs smaller than 200 ms or larger than three *SD*s of the individual mean were regarded as outliers, leading to total exclusion of 2% of the data. Effect sizes in the present and the following experiments are reported by partial η^2, reflecting the proportion of variance accounted for by the effect relative to the sum of its variance and the error variance.

Sequential RTs. An analysis of variance (ANOVA) was conducted on the sequential updating RTs with session (one- twelve) and task (numerical vs. spatial) as within-subject factors and compatibility (compatible vs. incompatible spatial S-R mapping group) as between-subject factor. The results are summarized in Table 3.1 and displayed in Figure 3.3. The RTs decreased with practice and were longer for the numerical than for the spatial task. The practice effect was stronger for the numerical than for the spatial task. Most important there was no effect of compatibility on the sequential updating: RTs were similar for the two tasks across the two groups. There was a significant three-way interaction showing that the practice effect of the spatial task for the incompatible mapping group was stronger than the practice effect for the spatial task of the compatible mapping group. No such practice difference between the mapping groups was observed for the RTs of the numerical task.

Due to the interactions with the task factor separate analyses for the RTs of the numerical and the spatial tasks were conducted (see Table 3.2). The results confirmed the overall analysis showing a significant practice effect for the numerical as well as for the spatial task. RTs in the numerical task did not differ between compatibility groups, confirming equal performance level for the groups. Though there was no main effect of compatibility in the spatial task, the interaction between session and compatibility was significant. The effect was small. As can be seen in Figure 3.3 there was an early advantage for compatible mapping group but practice compensated the compatibility benefit.

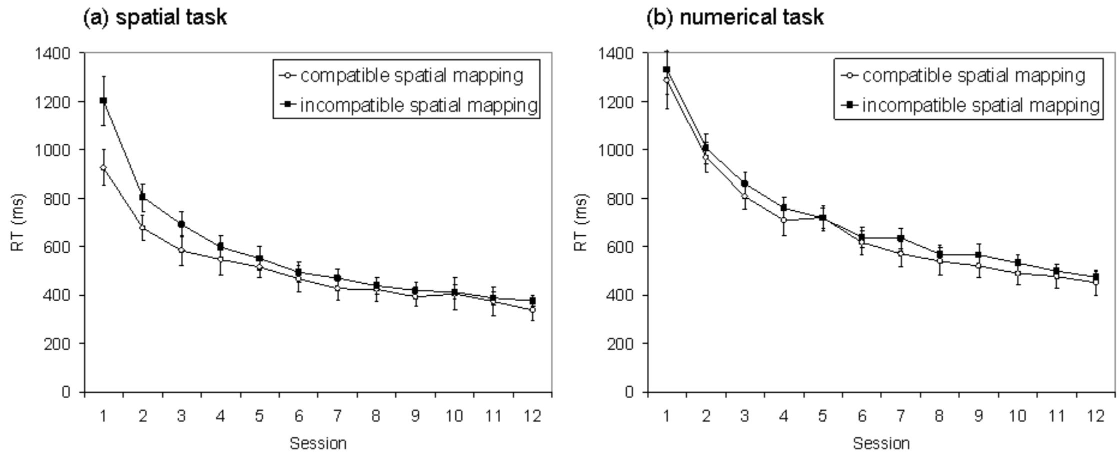

Figure 3.3. Spatial (a) and numerical (b) RTs of the compatible and the incompatible spatial mapping group for each session. Error bar represent one standard error of the mean.

Table 3.1 Summary of the ANOVA results on the sequential updating RTs.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	282.07 (1, 20)	.934	<.001
Session (quadratic)	93.13 (1, 20)	.823	<.001
Session*Compatibility (linear)	1.69 (1, 20)	.078	.208
Session* Compatibility (quadratic)	1.35 (1, 20)	.063	.259
Task	32.84 (1, 20)	.621	<.001
Task* Compatibility	.25 (1, 20)	.021	.623
Task*Session (linear)	12.63 (1, 20)	.387	.002
Task*Session (quadratic)	2.36 (1, 20)	.106	.140
Task*Session* Compatibility (linear)	3.90 (1, 20)	.163	.062
Task*Session* Compatibility (quadratic)	9.18 (1, 20)	.315	.007
Compatibility	.70 (1, 20)	.034	.413

Note. In the table above as in following tables if reported the contrasts for the effects are specified in brackets being quadratic or linear.

Table 3.2 Summary of the separate ANOVA results on the numerical and spatial sequential updating RTs.

Effect		F(df)	partial $\eta 2$	p
num	Session (linear)	284.19 (1, 20)	.934	<.001
	Session (quadratic)	99.99 (1, 20)	.833	<.001
	Session* Compatibility (linear)	.03 (1, 20)	.001	.870
	Session* Compatibility (quadratic)	<.01 (1, 20)	<.001	.970
	Compatibility	.28 (1, 20)	.014	.605
spat	Session (linear)	156.72 (1, 20)	.887	<.001
	Session (quadratic)	64.77 (1, 20)	.764	<.001
	Session* Compatibility (linear)	4.19 (1, 20)	.173	.054
	Session* Compatibility (quadratic)	4.43 (1, 20)	.181	.048
	Compatibility	1.03 (1, 20)	.049	.323

Dual-task costs in RTs. As in Experiment 1 dual-task costs were the difference of the observed updating RTs in the simultaneous condition minus the maximum sequential RTs (i.e. the predictions for parallel processing). Positive values indicated a deviation from parallel processing that is dual-task costs.

The dual-task costs were analyzed in an ANOVA with session (one- twelve) as within-subject factor and compatibility (compatible vs. incompatible spatial S-R mapping group) as between-subject factor (see Table 3.3). As predicted by the supervision-based crosstalk assumption the incompatible group exhibited about 210 ms higher dual-task costs (*M*: 505.35 ms, *SD*: 139.19) than the compatible group (*M*: 294.94 ms, *SD*: 93.99). Figure 3.4 shows decreasing dual-task costs with practice. Nevertheless, the residual dual-task costs for the last session differed significantly from zero for both, the incompatible (*M*: 258 ms, *SD*: 95.46), $t(11)=9.36$, $p<.001$, and the compatible group (*M*:147 ms, *SD*: 81.68), $t(9)= 5.68$, $p<.001$.

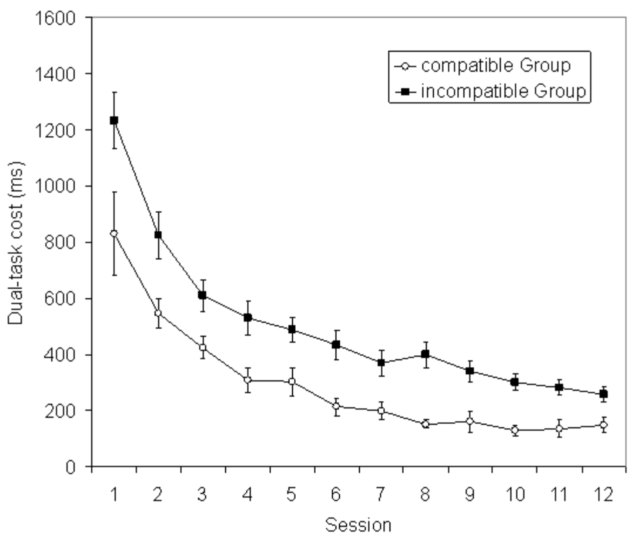

Figure 3.4. Dual-task costs in RTs for the compatible and the incompatible group for each session. Error bars represent standard errors of the mean.

Table 3.3. Summary of the ANOVA results on the dual-task costs in RTs.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	149.48 (1, 20)	.882	<.001
Session (quadratic)	78.65 (1, 20)	.797	<.001
Session* Compatibility (linear)	2.76 (1, 20)	.121	.112
Session* Compatibility (quadratic)	.52 (1, 20)	.025	.480
Compatibility	16.51 (1, 20)	.452	.001

Sequential PEs. Corresponding to the analysis of the sequential RTs, PEs were subjected to an ANOVA with session (one- twelve) and task (numerical vs. spatial) as within and compatibility as between-subject factor. The results are summarized in Table 3.4. The compatibility factor did not affect PEs. Hence, overall single-task performance did not differ between the compatibility groups despite their different spatial S-R mapping. Practice benefitted performance. Furthermore, there was a less interesting three-way interaction showing that whereas the spatial task errors of the incompatible mapping group decreased for the first sessions and stayed constant for the remaining sessions, the spatial errors of the compatible group rather increased for the last sessions. No such difference in practice effects on errors between the compatibility groups was observed for the numerical task.

Table 3.4 Summary of the ANOVA results on the sequential PEs.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	2.04 (1, 20)	.093	.168
Session (quadratic)	6.01 (1, 20)	.231	.024
Session* Compatibility (linear)	2.09 (1, 20)	.095	.163
Session* Compatibility (quadratic)	.47 (1, 20)	.023	.501
Task	.72 (1, 20)	.035	.405
Task* Compatibility	2.71 (1, 20)	.119	.115
Task*Session (linear)	1.78 (1, 20)	.082	.197
Task*Session (quadratic)	8.06 (1, 20)	.287	.010
Task*Session* Compatibility (linear)	.24 (1, 20)	.012	.630
Task*Session* Compatibility (quadratic)	8.04 (1, 20)	.287	.010
Compatibility	1.26 (1, 20)	.059	.276

Separate analyses for the tasks demonstrated that practice had an effect on the spatial task only, with a small initial decrease in errors (see Table 3.5). There was a marginal significant interaction of group and session, showing that the PE distribution of the incompatible mapping group across sessions was U-shaped whereas it had an inverted U-shape for the compatible group.

The factor compatibility had no influence on the spatial task PEs, failing to reach the conventional levels of significance (see Table 3.5). As described in the overall analysis, the spatial PEs only decreased for the first four sessions and then reached an asymptote.

Table 3.5 Summary of the separate ANOVA results on the numerical and spatial sequential updating RTs.

Effect		*F*(df)	partial *η2*	*p*
num	Session (linear)	.15 (1, 20)	.008	.701
	Session (quadratic)	.16 (1, 20)	.008	.691
	Session* Compatibility (linear)	.89 (1, 20)	.043	.356
	Session* Compatibility (quadratic)	4.21 (1, 20)	.174	.054
	Compatibility	.10 (1, 20)	.005	.752
spat	Session (linear)	3.31 (1, 20)	.142	.084
	Session (quadratic)	14.82 (1, 20)	.426	.001
	Session* Compatibility (linear)	1.86 (1, 20)	.085	.188
	Session* Compatibility (quadratic)	1.20 (1, 20)	.056	.287
	Compatibility	3.24 (1, 20)	.140	.087

Dual-task costs in PEs. Dual-task costs in errors were computed as the difference between mean PEs in the simultaneous condition (averaged across tasks) and the mean PEs in the sequential condition. Dual-task costs in PEs were subjected to an ANOVA with session (one- twelve) as within-subject factor and compatibility (compatible vs. incompatible spatial mapping) as between-subject factor. The results are listed in Table 3.6. Overall dual-task costs in errors were very low (*M*: .006, *SD*: .02). They reduced with practice. There was no difference in the dual-task costs in errors between the compatibility groups. Hence, there was no speed-accuracy trade off for the S-R mapping effect in dual-task performance.

Table 3.6. Summary of the ANOVA results on the dual-task costs in PEs.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	8.80 (1, 20)	.305	.008
Session (quadratic)	4.11 (1, 20)	.170	.056
Session* Compatibility (linear)	1.70 (1, 20)	.078	.207
Session* Compatibility (quadratic)	.77 (1, 20)	.037	.390
Compatibility	.25 (1, 20)	.012	.621

Parallel processing. To classify participants into parallel or serial processors after practice, the dual-task costs in RTs and PEs of the last three training sessions were analyzed (as described in the Result section of Experiment 1). Following the criterion introduced by Göthe, Oberauer and Kliegl (2007), dual- task costs had to be non-significant without a speed-accuracy trade-off in two of the three relevant sessions to classify a participant as a parallel processor. Otherwise participants were classified as serial processors. In the present experiment only one participant could be classified as a parallel processor. This was Participant A of the compatible mapping group. Table 3.7 displays the mean RTs and PEs as well as the test statistics for the last three training blocks of this participant. All other participants of the compatible and the incompatible mapping group were serial processors. Table A1 in the Appendix A summarizes the data and the test statistics for the last three training blocks of the serial processors. Figure 3.5 shows the mean RTs of the simultaneous condition and the max(seq) RTs as well as the mean PEs of the simultaneous and the sequential condition for each training session of Participant A from the compatible mapping group. To put the small number of parallel processors in this experiment into perspective, one has to take into account that there was less practice in Experiment 2 than in previous studies (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) using the same verbal-numerical and a very similar spatial task. In the present experiment the participants received 480 (12*40) dual-task trials and in the previous studies at least 640 (8*80) up to 960 (12*80) dual-task trials practice. Note also, that the participants of Experiment 2 practiced both, sequential and simultaneous updating in one session, whereas conditions were compared between different sessions in the earlier studies. Consequently, twelve session samples were compared in Experiment 2- as in the Oberauer and Kliegl study, but each session based upon less observations.

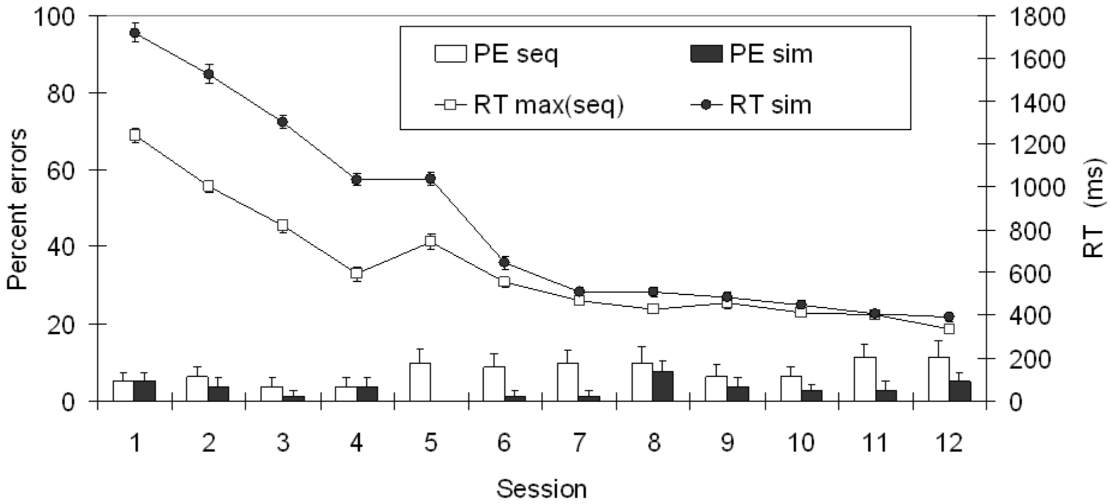

Figure 3.5. Training data of Participant A of the compatible mapping group who trained for a whole of twelve sessions. Mean RTs (left y-axis) for the simultaneous condition (RT sim) and the maximum sequential RTs (RT max(seq)) are given by session. Error bars represent standard errors of the mean. Percentages of errors (right y-axis) for each training block are averaged across tasks (numerical, spatial) for the simultaneous (PE sim) and the sequential condition (PE seq).

Table 3.7. Mean RTs, PEs and test statistics for the last three training blocks of Participant A of the compatible mapping group. In brackets SDs are given for the RTs and the PEs.

Session	RT			PE		
	Max (seq)	Sim	*T*(df)/	Seq	Sim	$\chi 2$
10	414 (89)	446 (137)	-1.20 (64.01)	6.25 (16.75)	2.50 (11.04)	1.41
11	401 (114)	408 (93)	-.29 (68)	11.25 (21.15)	2.50 (15.81)	10.91*
12	334 (78)	390 (111)	-2.42 (67)*	11.25 (26.52)	5.00 (15.19)	2.24

Note: Mean RTs are in milliseconds. In the sequential condition, max(seq) RTs are given. Test statistics are *T* values) for RTs with degrees of freedom (df) in brackets and $\chi 2$ values for PEs. Test statistics are marked with an asterix if t-tests or $\chi 2$-tests approach a significance level of $p< 0.05$.

3.3. Discussion

Experiment 2 examined whether the dual-task performance of two tasks, both containing non-compatible S-R mappings, is reduced with respect to a situation where at least one task contains a compatible S-R mapping. Therefore, two dual-task groups practiced one verbal together with one spatial task. The two groups differed only in the S-R mapping of the spatial task being compatible for one and incompatible for the other group. The verbal task contained an arbitrary S-R mapping for both groups. The results demonstrated that costs were significant for both groups at the end of practice (compatible group: 147 ms, $t(9)=5.68$, $p<.001$), incompatible group: 258 ms, $t(11)=9.36$, $p<.001$). However, dual-task costs were higher for the incompatible compared to the compatible S-R mapping group. This S-R mapping effect on dual-task costs cannot be attributed to higher difficulty of the incompatible compared to the compatible mapping of the spatial task, because performance level of the single tasks was the same across groups (at least after some practice).

Hence, irrespective of the mapping group for most of the participants (except for Participant A of the compatible mapping group) a functional bottleneck was active since dual-task costs could not be eliminated. However, the bottleneck delay was longer for the incompatible compared to the compatible mapping group. This difference in dual-task performance between the S-R mapping groups is attributed to the difference in demand of top-down control for the two tasks. For the compatible mapping group the implementation of only one task, i.e. the verbal task had to be supervised by executive control, for the incompatible group, the implementation of both S-R mappings had to be supervised by executive control. When both tasks are under executive control, the separation of their signals might not be easily accomplished. Instead interactions might lead to errors, i.e. control signals designated to one task could be wrongly applied to the other.

One potential candidate to prevent or resolve the crosstalk of control signals is the process of task set reconfiguration, which is traditionally associated with the task switching literature (De Jong, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). In a task switching experiment two or more tasks are presented sequentially. People perform worse in each task when they have to switch between them compared to the situation when a task is repeated. This switch cost is assumed to reflect the time consumed by task set reconfiguration. Task set reconfiguration is a process that is associated with different mechanisms and might therefore imply several stages that all together not necessarily take place for each task switch (Monsell, 2003). As a common characteristic the mechanisms are associated with an endogenous executive control process that prepares for the upcoming task.

Adopting the task set reconfiguration for the present case it might reflect the suppression of the prior task set in use and the activation of the new task set. Thereby, it not necessary to assume this process exclusively taking place for the incompatible group. Possibly a task set reconfiguration stage was active after central processing of the respective Task 1 for both groups (except for Participant A). Nevertheless, its duration was lengthened for the incompatible group due to the higher control demand in both tasks and the resulting necessity for resolving crosstalk.

Comparison to earlier studies

As mentioned above Participant A of the compatible S-R mapping group was able to show perfect time sharing of the numerical and the spatial task. The low rate of parallel processors in the compatible group (one out of nine) was not expected, because parallel processing has been shown in previous studies using the same numerical task and an only slightly different spatial task with the same S-R mappings for nine out of twelve participants (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004). This difference in the parallel processing ability is partly due to the smaller practice opportunity in the present compared to the earlier studies. Whereas the individual dual-task practice opportunity included 480 dual-task trials in the present study the young participants in the study of Göthe, Oberauer and Kliegl (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) received 693 dual-task trials on average. However, examining the dual-task costs for a matched amount of practice (i.e. after the maximum practice opportunity given in the present experiment compared to practice after block 6 in the previous studies), dual-task costs were still considerably higher in the present (compatible group- *M*: 147 ms, *SD*: 81.68) compared to earlier studies (*M*: 24 ms, *SD*: 79.83), $t(20)= 3.55$, $p=.002$. This was true despite the fact that single-task RTs (for the matched practice level) were more than 100 ms faster in the present compared to previous studies. This was true for the numerical task (identical task), $t(20)= 2.12$, $p=.047$ (compatible group: *M*: 451 ms, *SD*: 160.54, previous study: *M*: 573 ms, *SD*: 107.64), as well as for the spatial task (small differences in design), $t(20)= 2.79$, $p=.011$ (compatible group: *M*: 337 ms, *SD*: 139.15, previous study: *M*: 480 ms, *SD*: 102.59). This difference in single-task performance (in particularly for the numerical task, which was identical) demonstrates that the participants of the compatible group of the present experiment outperformed the participants of the previous study in single-task performance but fell short in parallel processing ability.

Content-based crosstalk

Next to the lesser practice opportunity in the present compared to earlier experiments (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) there is one further factor that could explain the higher overall dual-task costs. This is the potential for content- based crosstalk between the two tasks, i.e. code confusability due to representational overlap between the tasks. Content-based crosstalk could be reduced to a minimum in the former studies (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004), but might have been higher for the present task combination. In the present experiment the spatial task was to shift the dot position one or two steps into the displayed direction, which was indicated by one or two arrows. The numerical task was to subtract one or add two to an actual number in mind. Hence, the updating stimuli of both tasks might have included the representation of the quantities one or two. The potential representational similarity between the tasks could have enhanced crosstalk between them, i.e. the quantity input of one task could have be wrongly used as the quantity input for the other task. This in turn could have promoted a serial processing strategy to prevent errors for most of the participants. This might has increased dual-task costs in RT compared to earlier studies. Next to the spatial shifting in numbers of section units the participants could also solve the spatial task in shifting the dot position a short or a long distance, which should reduce representational crosstalk. This is possibly a way how Participant A reached less dual-task interference.

The content-based crosstalk nevertheless cannot explain the differences in dual-task costs between the groups. Assuming content-based crosstalk it should be present in both groups since groups to the same extent. In both groups the quantities one and two had to be applied to both tasks, which constitutes the potential of content-based crosstalk.

Conclusion

Experiment 2 demonstrated that the need for executive control of two tasks influences their parallel processing potential. This adds to previous evidence in Experiment 1 that despite equal single-task performance and practice opportunity the dual-task costs are higher for groups with two non compatible S-R mapping tasks compared to groups with at least one compatible S-R mapping task. Such a result is contrary to the prediction of the bottleneck account, which predicts equal dual-task costs for groups with equal single-task performances. The crosstalk account represents a viable explanation for this finding. It postulates that the potential of confusion between the executive control signals of two tasks induces a serial processing strategy in order to reduce potential task errors.

4. Experiment 3 –Dual-task processing of S-R and C-R modality-pairing groups over practice within a SPP

Recent time controlled experiments (Hazeltine & Ruthruff, 2006; Hazeltine, Ruthruff, & Remington, 2006; Ruthruff, Hazeltine, & Remington, 2006; Stelzel, Schumacher, Schubert, & D'Esposito, 2005) confirmed early observations (Shaffer, 1975) that input-output modality-pairings in stimulus-response assignments affect dual-task performance. This effect cannot be attributed to differences in single-task performances. Combining on the one hand a visual-manual together with an auditory-vocal task produces higher dual-task costs than interchanging modality pairings and combining on the other hand a visual-vocal together with an auditory-manual task. Thereby, in the first case the input-output modality-pairings of the two tasks are declared as Standard modality-pairings (S) or modality compatible. In the second case the modality pairings of the two tasks are declared as Non Standard modality-pairings (NS) or modality incompatible.

Experiment 3 tests whether the higher dual-task costs for two Non Standard compared to two Standard S-R modality-pairing tasks can be explained through between-task crosstalk for the Non Standard tasks. The crosstalk happens due to representational overlap between the stimulus features of one and response features of the other task, which are coded in a common medium. The common coding of stimuli and response features is formulated in the theory of event coding (TEC, Hommel, Müsseler, Aschersleben, & Prinz, 2001). The present aim was to demonstrate that with the appropriate feature maps representing the two tasks the S-R modality-pairing effect could be reversed, showing that in a particular case two Standard S-R modality-pairing tasks exhibit higher dual-task interference than two Non Standard modality-pairing tasks.

In an early experiment Shaffer (Shaffer, 1975), found evidence for the effect of modality pairings on the magnitude of dual-task costs. In this single subject study of a skilled typist, Schaffer observed that typing of a visually presented text only interfered little with shadowing of auditory presented words, while typing of an auditory presented text strongly interferes with reading aloud visually presented words. Shaffer suggested that “there is a natural compatibility of input and output modes which is not critically important for single tasks but becomes so for dual” (Shaffer, 1975, p. 164).

This modality-pairing dependency of dual-task costs was also found in more recent and time controlled PRP experiments. In the experiment of Hazeltine and Ruthruff (Hazeltine & Ruthruff, 2006), for example, the modality compatible task pair included a left or right key press to the visually presented symbols ‘#’ and ‘%’ and saying “one” or ”two” to the presentation of two possible tone pitches, i.e. a visual-manual and an auditory-vocal task, respectively. The modality incompatible task pair demanded to press a left or right key according to the pitch of a tone and to speak “one” or “two” aloud according to the visual symbols ‘#’ or ’%’, i.e. an auditory-manual and a visual-vocal task, respectively. The tested dual-task groups practiced either the modality compatible or the modality incompatible task pair. Furthermore, groups differed in the order of presentation of the two tasks in the PRP paradigm, resulting in four different dual-task groups. Whereas modality pairings only slightly affected single-task performance, dual-task costs dramatically varied with the modality pairings. Higher costs were observed for modality incompatible pairing groups compared to modality compatible pairing groups. The authors suggested that, the results argue against a modality independent central resource that has to be successively allocated to the central response selection stages of both task as the central bottleneck theory postulates. Instead Hazeltine and Ruthruff propose interference between the central operations as the underlying mechanism for higher dual-task interference in modality incompatible groups.

The present experiment wants to show that the basis for this central interference is features that are shared between the representations of both tasks. In the following part of the introductory section the underlying architecture for this prediction is sketched: the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1990). Moreover, its application to the dual-task context and therein to the modality-pairing effects on dual-task costs is explained. Subsequently, I introduce the present experimental design including four different modality-pairing groups. The predictions of the TEC with respect to the dual-task costs are given.

A feature based account of modality-pairing effects on dual-task interference

Assuming central interference as the source of modality-pairing effects on dual-task performance, Hazeltine and Ruthruff (Hazeltine & Ruthruff, 2006) explicitly refer to the TEC as a representational architecture for these effects. The TEC was specified by Hommel and colleagues (Hommel, Müsseler, Aschersleben, & Prinz, 2001). Its fundamental basis is the common coding principle. It comprises that stimuli and responses are represented in a common medium (Prinz, 1990). The general basis for representations consists of features. A combination of certain features can internally map different aspects of one distal event and thus is applicable to both incoming stimuli and produced responses. Relevant features of perceptual events and the accompanied actions are activated and bound together according to the current task context. These integrated representations are named event-codes. Within an event code the representations associated with the stimulus and the response may or may not share features they are composed of.

In dual-task context two event codes have to be established, i.e. the stimulus and the response features of two tasks are activated and have to be bound correctly to each other. In this situation, not only the stimulus and response representations of one task can overlap, but also across tasks if task representations are similar. This representational overlap is the basis for interactions across tasks.

How can the common coding of the TEC framework explain S-R modality-pairing effects on dual-task costs as found in Hazeltine and Ruthruff (2006)? When looking at the feature maps that represent stimuli and responses in this study the Standard modality-pairing group worked on a visual-manual task that contained the visual categorization of the '#' and '%' signs with a spatial left or right key press. Hence, the spatial features of the visual stimuli had to be translated into a spatial response. Naturally, you can hardly describe visual input and a manual response without using spatial coordinates. The visual and the manual modalities by nature share spatial features. The auditory-vocal task in Hazeltine and Ruthruff included the categorization of two tones according to their pitch with the utterances of saying "one" or "two". For this task sonic features are shared between auditory stimuli and the vocal responses. Hence, for the Standard modality-pairing tasks spatial and sonic information are part of different tasks. When interchanging the modality pairings in the Non Standard modality-pairing condition spatial and sound features, however, now belong to both tasks.

Whereas feature activation should be identical between the modality-pairing conditions (stimuli and responses were identical for the groups) the results of the binding processes for the two tasks are different. For Standard modality-pairing tasks the concurrent binding processes rely on distinct representational dimensions- in the example on spatial features for one task and sonic features for the other task. The idea is that tasks are easy to distinguish when either their stimuli or their responses do not overlap on a common representational dimension, i.e. their binding processes can work without conflict. For Non Standard modality-pairings representational overlap between the tasks exists, i.e. spatial and sonic features are part of both event codes. This increases the potential of crosstalk between the two tasks. Crosstalk means the confusion of S and R codes across tasks. When crosstalk happens something has to be done to reverse it in order to keep errors minimal or to avoid it at the outset. Both lead to longer dual-task processing times. This potential of mutual crosstalk during S-R binding is the basis for the higher dual-task costs for Non Standard compared to Standard modality-pairing tasks.

The present experiment: S-R and C-R modality-pairings

The present study wants to test the predictions of the TEC model explaining modality-pairing effect in dual tasks though feature-based crosstalk. The aim is to demonstrate that the feature representations behind the modality pairings (either overlapping between tasks or not) are responsible for the observed modality-pairing effect on dual-task costs. Therefore, a new term is introduced: central representation codes (C codes). So far, in order to explain modality-pairing effects on dual-task costs the representations of stimulus and response modalities have been regarded. The intermediate features that are supposed to produce the crosstalk for Non Standard modality-pairings were spatial and verbal features being part of the stimulus representation of one task and the response representation of the other task. Therefore, in the following, stimulus features that are task relevant (i.e. stimulus features that have to be evaluated to fulfil the task) being either spatial or verbal-sonic in nature, will be defined as the central feature codes. The dual-task groups used in the present experiment are in the following illustrated together with this new classification[2]. Consequently, the modality of the C-codes is included in the taxonomy of modality-pairings, which is extended to S-C-R modality-pairings3. Table 4.1 gives an example for the S-C-R modality specification for the dual-task groups used in present Experiment 3.

At first let us focus on Group 1 and 4. These groups work on two Standard (Group 1) or two Non Standard S-R modality-pairing tasks (Group 4). As can be seen in the table, Task 1 of Group 1 includes responding according to the visual presentation of one of three possible stimulus locations with a spatially corresponding manual key press. The relevant feature of the stimulus, i.e. the C-code that has to be evaluated is the spatial position. Therefore, the modality of the C-codes for Task 1 is the spatial modality. The central modality for Task 2 is the verbal modality, because the pitches of the tones have to be evaluated. At this point the classification of non linguistic tones to the verbal domain shows the limits of the taxonomy of C-codes modality. Strictly speaking, it is just the acoustic information that it is necessary to react on. Nevertheless, there are findings that cortical networks associated with language

2 However, it is necessary to note that in the event code specification used in the TEC there is no specification of a C- code. The term is just introduced for the present purpose to test representational overlap across tasks being a source of dual-task costs.

3 The S-C-R compatibility term originally refers to the multiple resource theory of Wickens (Wickens, 1980). There is no theoretical correspondence to the present account as it only serves as taxonomy for feature overlap in the present context.

processing were also found to serve the processing of acoustic music (Koelsch et al., 2002). For simplicity, the label of verbal vs. spatial C-codes is kept since it has no influence on the theoretical implication. Focussing Group 4, it becomes clear that S-R assignments of Group 1 were simply crossed to build up the tasks of Group 4. Hence, Task 1 includes a vocal response according to the spatial localisation (spatial C-code) of visual stimuli. The manual response of Task 2 is associated with the verbal discrimination (verbal C-code) of auditory stimuli, i.e. to press a key according to the pitch of a tone.

Table 4.1. List of the tasks for the S-R and C-R modality-pairing groups of Experiment 3.

Group	S-R Pairs	C-R Pairs	Tasks	Stimulus/ (Modality)	Central/ (Modality)	Response/ (Modality)
1	S	S	1	o o o (visual)	circle location (spatial)	three choice key press (manual)
			2	two tones (auditory)	tone pitch (verbal)	"one", "two" (vocal)
2	NS	S	1	A B C (visual)	letter identity (verbal)	"one", "two", "three" (vocal)
			2	one tone (auditory)	tone location (spatial)	two choice key press (manual)
3	S	NS	1	ABC (visual)	letter identity (verbal)	three choice key press (manual)
			2	one tone (auditory)	tone location (spatial)	"one" or "two" (vocal)
4	NS	NS	1	o o o (visual)	circle location (spatial)	"one", "two", "three" (vocal)
			2	two tones (auditory)	tone pitch (verbal)	two choice key press (manual)

Note. S and NS in column two and three refer to the classification of S-R and C-R pairs of the tasks as Standard or Non Standard, respectively.

With the introduction of the C-code modality, not only S-R pairings but also of the C-R modality-pairings can be classified into Standard vs. Non Standard pairings. Therefore, in addition to the nature of the S-R modality-pairings (Table 4.1, column two) the nature of the C-R modality-pairings for each tasks of each dual-task group is displayed in column three of Table 4.1. In analogy to S-R modality-pairing classification, C-R modality-pairing classifications are originated from the presence or absence of representational overlap between the constituting modalities. Therefore, a spatial-manual pairing shares spatial features and a verbal-vocal pairing shares sonic features. Both are Standard C-R modality-pairings. Non Standard C-R modality-pairings comprise of the spatial-vocal and the verbal-manual pairings. Re-examining the S-R and C-R pairings given in Table 4.1, it becomes obvious that the C-R modality-pairings are also Standard pairings for the Standard S-R modality-pairing tasks of Group 1. For the Non Standard S-R modality-pairing tasks of Group 4 the C-R modality-pairings are also Non Standard. That means that in the present example the change from Standard to Non Standard S-R pairings from Group 1 to 4 is confounded with a change in C-R pairings from Standard to Non Standard.

Since C-codes are currently defined as the task relevant features of the stimulus their pairing to the response modality should comprise a significant part of the representational overlap between stimuli and responses. Therefore, it is predicted to be mainly responsible for modality-pairing effects on dual-task costs. That is, when C-R modality-pairings are Non Standard for two combined tasks the representational overlap between them should increase dual-task interference compared to the absence of representational overlap between two Standard C-R modality-tasks. With the current task design, however, the C-R modality-pairings can be manipulated independently of S-R pairings.

De-confounding the observed S-R and C-R pairing-dependency in the example two additional dual-task groups are established: one with Standard C-R pairings but Non Standard S-R pairings (Group 2) and one with Non Standard C-R pairings but Standard S-R pairings (Group 3). Table 4.1 gives the example for these two additional groups. Task 1 of Group 2 contains visual stimuli, the letters “A”, “B”, or “C”. Here, the task is to identify the letter, which makes the verbal features of the visual stimuli relevant (verbal C-code) and to respond to them with the words “one”, “two” or “three” (vocal-R-code), respectively. Task 2 contained the auditory presentation of a tone at the left or the right side of the earphones. The location has to be determined (spatial C-code) and the spatially compatible key had to be pressed (manual R-code).

Group 3 is the group with Standard S-R but Non Standard C-R modality-pairings. Task 1 of Group 3 contains the visual presentation of the letters “A”, “B” or “C”. The letter identity (verbal C-codes) has to be classified by pressing one of three possible keys (spatial R-code). Task 2 is to define the location of a tone (spatial C-code) by saying either “one” or “two” (verbal R-code) according to the presentation of a tone in the left or the right ear, respectively.

Taken together, in all four groups two tasks are given that are composed of the same sets of stimulus modalities (visual vs. auditory), the same sets of central modalities (spatial vs.

verbal) and the same sets of response modalities (manual vs. vocal). However, the groups differ in S-R and C-R modality-pairings of both tasks being either Standard or Non Standard. Standard pairings were pairings for which the two modalities of each task included either spatial or verbal features. Non Standard pairings were pairings for which the two modalities of each task included both spatial and verbal features. The S-R and C-R modality-pairings are varied independently over groups thus forming a factorial combination. The differential effect of S-R and C-R pairings on dual-task costs is tested. In the present experimental design the representational overlap between the task relevant features of the stimulus and the response features is carried by the C-R modality-pairings. The S-R pairings code the nature of the pairing between less relevant stimulus features coding the stimulus modality and the response features. Features coding the stimulus modality are less relevant because they are not directly needed to fulfil the task. For example, for Task 2 of Group 2 the relevant features of the stimulus are the spatial position of the tone. The less relevant feature is the auditory modality, i.e. the sound properties of the tone that is presented. This sound characteristic is moreover identical for the two possible tones that were presented in Task two. This sound characteristic is not obligatory to fulfil the task. It is therefore possibly not bound to the event code. Hommel (Hommel, 1993a, 1998b) could show that feature integration is not always complete and that task context, attention and relevance of features can modulate whether or not a feature is integrated in an event code. Hence in the present example, features coding the stimulus modality are not necessarily part of the binding and hence do not serve as the basis for potential overlap with the response features of the respectively other task. Once separated from the C-R pairing effect the S-R pairing effect should only have a minor influence on dual-task costs, however cannot be ruled out completely.

4.1. Method

Participants. The participants were 24 high school students from the University of Potsdam between 20 and 28 years (*M*= 22 years). They received five Euro per each 30 min session or course credit. They also earned points for fast and accurate responding which could be converted into extra monetary or course credit reward.

Design. The four tested groups trained two tasks- a vocal two choice task and a manual three choice task within a simultaneous presentation paradigm (SPP). The vocal responses were recorded via a microphone that was part of a headset. The manual responses were recorded via the computer keyboard. The training schedule was the same for all groups and started at the same time. The four groups trained different vocal and manual tasks. Table 4.1 lists the groups with their respective two tasks.

Participants of Group 1 (Standard (S), Standard (S)- for the S-R and C-R modality-pairings, respectively) trained an auditory-verbal-vocal task and a visual-spatial-manual task. In the auditory-verbal-vocal task participants heard one of two different 40 ms tones- a high pitch or a low pitch tone. They responded by saying the German words for “one” or “two”, respectively. In the visual-spatial-manual task they saw a circle in three possible locations (left, middle and right) on the computer screen. They had to determine the position of the circle by pressing the one, two or three key of the number pad of the keyboard. The positions of the circle were mapped spatialy compatible to the response keys (left- one, middle- two, right- three).

The participants of Group 2 (NS, S) trained a visual-verbal-vocal task together with an auditory-spatial-manual task. The visual stimuli in the visual-verbal-vocal task of Group 2 were the capital letters A, B or C presented in the middle of the screen. The corresponding reaction was to say aloud the German words for “one”, “two” or “three”, respectively. In the auditory-spatial-manual task of Group 2 a 40 ms- 990 Hz tone was presented. The tone was presented via earphones either to the left or the right ear. The participants had to press corresponding to the direction of the tone the one or the three on the numerical pad of the keyboard (the one is the rightmost number and the three is the leftmost number on the pad).

Group 3 (S, NS) trained an auditory-spatial-vocal tasks combined with a visual-verbal-manual task. In the auditory-spatial-vocal task a 990 Hz tone was presented via the left or the right earphone and the participants had to react vocally by saying “one” or “two”, respectively. In the visual-verbal-manual task they saw the letters A, B or C on the computer screen and had to press the one, two or three key, respectively on the number pad.

Group 4 (NS, NS) performed a visual-spatial-vocal task and an auditory-verbal-manual task. In the visual-spatial-vocal task the participants saw a circle in one of three possible positions on the screen and had to say “one”, “two” or “three”, respectively. In the auditory-verbal-manual task they heard a high or a low pitch tone and had to respond manually by pressing the one or the three, respectively on the number pad of the keyboard.

All groups trained their respective two tasks for eight sessions. Every session included three practice blocks followed by twelve test blocks. The test blocks were composed of one single-task block of one task followed by two mix blocks consisting of randomly intermixed dual-task and single-task trials of both tasks and then again one single-task block of the other task. This sequence of four blocks was replicated three times forming the series of twelve test blocks including six mix blocks and six single-task blocks (three for each single task). The order presenting the two single-task blocks was constant within one session, reversed for the subsequent session and counterbalanced across participants. Each block included 60 trials. For a mix block the 60 trials consisted of twelve single-task trials of each task and 36 dual-task trials with an SOA of zero. The three practice blocks consisted of two single-task blocks (one for each task) including twelve trials each and a mix block with eleven trials (three visual single-task trials, two auditory single-task trials, six dual-task trials).

Procedure. At the beginning of each trial a fixation stimulus/ stimuli appeared for 500 ms. The groups with a visual-verbal task (Group two and three) saw one fixation cross in the middle of the screen. The groups with a visual-spatial task (Group one and four) saw three fixation lines for the three possible locations of the relevant stimuli on the screen. This was followed by the presentation of the respective visual and/ or auditory stimulus (depending on a single-task trial or a dual-task trial). The auditory stimulus was presented for 40 ms. The visual stimulus was displayed on the screen until the required reaction was given. In dual-task trials both stimuli, visual and auditory were displayed simultaneously. A dual-task trial was only completed if one manual and one vocal response were given. After the corresponding reaction/ reactions (in the case of a dual-task trial) the screen got blank and an inter trial interval of 1000 ms followed. After each block participants could make a short break. The mean RT and the percent correct rate of the respective manual task was presented. For the vocal task the percent correct were determined after the experiment by comparing the recorded sound files of each session with the proper responses. Prior to the next session the participants were informed about their accuracy in the vocal task.

Participants were instructed to respond as fast and as accurately as possible to each task. No task was declared as “Task 1”. Participants were not restricted in the order of responding in the dual-task blocks. However, they should give each answer immediately after completion.

Before each block the RT deadline was shown. The deadline corresponded to the mean RT of the preceding block of the same condition. The initial deadline in every condition (for each single-task block as well as the dual-task block) was 2000 ms. Participants were instructed to meet the deadline although the trial was not aborted in case the deadline was exceeded. According to the critique of Tombu and Jolicoeur (2004) the applied deadlines were different for the two single-task (vocal and manual tasks) and for the dual-task trials.

Participants got bonus after each session. The participant earned five points for falling below the RT deadline of the respective block. They lost five points for exceeding the deadline of the block with their mean RT. They also could earn three points for every percent correct point above 90% for each task averaged over one session. Three points were lost for each percent point under 90% correct for each task averaged over one session. Each point could be exchanged into 0.01 Euro or 0.1 minute. The bonus amounted up to additional 1.50 Euro per session or 15 minutes course credit.

4.2. Results

Trials with errors on either task were excluded from further analyses. Also excluded were RTs that were faster than 200 ms or slower than three *SD*s from the individual mean of that session, task and condition. The procedure resulted in the exclusion of 2.7% of the data. In the following the two tasks were classified according to their output modality, analyzing the effects on a manual and a vocal task.

Single-task RTs. RTs of the single-task blocks were submitted to an ANOVA with task (manual vs. vocal) and session (one to eight) as within-subject factors and S-R pairing (S-R Standard vs. Non Standard) and C-R pairing (C-R Standard vs. Non Standard) as between-subject factors. Table 4.2 summarizes the results of the tested effects. Responses to manual tasks were faster (*M*: 360 ms) than to the vocal task (*M*: 497 ms). Participants responded faster with practice (linear and quadratic contrast). The vocal task exhibited a stronger practice effect than the manual task (linear and quadratic contrast). The main effects of S-R pairing and C-R pairing just missed the conventional level of significance. Contrary to the expectation there was the tendency that the S-R Standard pairings tasks had longer RTs than the S-R Non Standard pairings. The C-R pairing factor showed the opposite but hence predicted trend with the C-R Standard pairings yielding shorter RTs than the C-R Non Standard pairings. There was no significant interaction of the S-R and C-R effect. The interaction of task x S-R pairing and of task x C-R, were significant. The manual tasks showed a stronger S-R and a stronger C-R pairing effect than the vocal task. The significant three way interaction of session (linear contrast) x task x S-R indicated stronger differences in the practice gains between the vocal and the manual task for the S-R Standard pairings than for the S-R Non Standard pairings. The session (linear contrast) x task x C-R pairing interaction was also significant. This was due to a stronger difference in the practice effects between the vocal and the manual task in the C-R Standard condition compared to the practice gain difference between the vocal and the manual task in the C-R Non Standard condition. To clarify the task specific effects, separate ANOVAs for each task were conducted.

Table 4.2. Summary of the ANOVA results on the single- task RTs of the single-task blocks as a function of output modality, session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	31.21 (1, 20)	.609	<.001
Session (quadratic)	10.26 (1, 20)	.339	.004
Session *SR	.48 (2.945, 58.893)	.023	.694
Session *SR (linear)	.89 (1, 20)	.043	.356
Session *SR (quadratic)	.34 (1, 20)	.017	.566
Session*CR	.55 (2.945, 58.893)	.027	.648
Session*CR (linear)	.06 (1, 20)	.003	.806
Session*CR (quadratic)	1.84 (1, 20)	.084	.190
Session*SR*CR	.81 (2.945, 58.893)	.039	.491
Session*SR*CR (linear)	.74 (1, 20)	.035	.401
Session*SR*CR (quadratic)	.55 (1, 20)	.027	.401
Output modality	336.29 (1, 20)	.944	<.001
Output modality *SR	60.34 (1, 20)	.751	<.001
Output modality *CR	61.42 (1, 20)	.754	<.001
Output modality *SR*CR	.075 (1, 20)	.004	.787
Output modality *Session	2.32 (2.949, 58.985)	.104	.085
Output modality *Session (linear)	7.79 (1, 20)	.280	.011
Output modality *Session (quadratic)	8.59 (1, 20)	.301	.008
Output modality *Session *SR	2.45 (2.949, 58.985)	.004	.074
Output modality *Session *SR (linear)	11.85 (1, 20)	.372	.003
Output modality *Session *SR (quadratic)	2.39 (1, 20)	.107	.138
Output modality *Session*CR	2.85 (2.949, 58.985)	.125	.046
Output modality *Session*CR (linear)	16.59 (1, 20)	.453	.001
Output modality *Session*CR (quadratic)	1.50 (1, 20)	.070	.236
Output modality *Session*SR*CR	1.27 (2.949, 58.985)	.059	.295
Output modality *Session*SR*CR (linear)	3.72 (1, 20)	.157	.068
Output modality *Session*SR*CR (quadratic)	.65 (1, 20)	.032	.429
SR	3.74 (1, 20)	.158	.067
CR	3.96 (1, 20)	.165	.060
SR*CR	.27 (1, 20)	.013	.610

Note. In the table above as in following tables if reported the contrasts for the effects are specified in brackets being quadratic or linear. Noninteger degrees of freedom arise from the Greenhouse-Geisser correction.

Manual single-task RTs. The results for the ANOVA on the manual single-task RTs are shown in Table 4.3. Figure 4.1a displays the manual RTs as a function of S-R and C-R modality-pairing. The manual tasks got faster with practice (linear contrast). The manual S-R Standard tasks were about 100 ms slower than the S-R Non Standard tasks. The C-R Standard groups showed significantly shorter RTs than the C-R Non Standard groups. The interaction of S-R and C-R pairing was not significant.

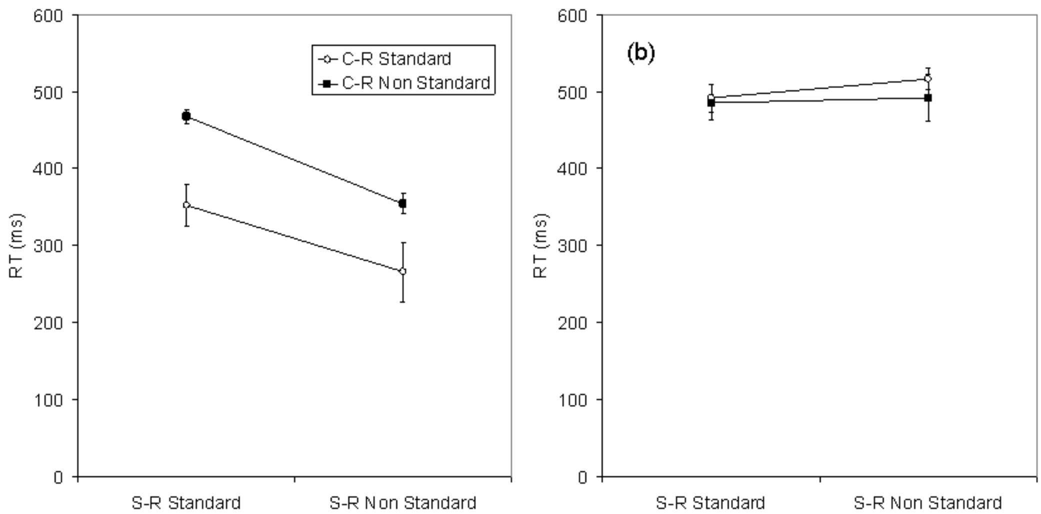

Figure. 4.1. Mean RTs of (a) the manual and (b) vocal single task as a function S-R and C-R modality-pairing. Error bars represent standard errors of the mean.

Table. 4.3. Summary of the ANOVA results on the manual single-task RTs as a function of session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	23.34 (1, 20)	.539	<.001
Session (quadratic)	2.86 (1, 20)	.125	.106
Session *SR	.47 (1.720, 34.401)	.023	.602
Session *SR (linear)	.42 (1, 20)	.021	.525
Session *SR (quadratic)	.14 (1, 20)	.007	.714
Session*CR	1.01 (1.720, 34.401)	.048	.365
Session*CR (linear)	3.00 (1, 20)	.130	.099
Session*CR (quadratic)	.53 (1, 20)	.026	.474
Session*SR*CR	.63 (1.720, 34.401)	.030	.517
Session*SR*CR (linear)	<.001 (1, 20)	<.001	.999
Session*SR*CR (quadratic)	09 (1, 20)	.005	.762
SR	23.34 (1, 20)	.539	<.001
CR	24.16 (1, 20)	.547	<.001
SR*CR	.412 (1, 20)	.020	.528

Vocal single-task RTs. The same analysis was done for the vocal single-task RTs. The effects are listed in Table 4.4. Figure 3.1b displays the vocal single-task RTs as a function of S-R and C-R pairing. Except a significant practice effect on vocal single-task RTs (linear and quadratic contrast), no other effects reached the level of significance.

Table. 4.4. Summary of the ANOVA results on the vocal single-task RTs as a function of session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	29.41 (1, 20)	.595	<.001
Session (quadratic)	12.59 (1, 20)	.386	.002
Session *SR	1.69 (4.349, 86.971)	.078	.155
Session *SR (linear)	3.86 (1, 20)	.162	.068
Session *SR (quadratic)	1.16 (1, 20)	.055	.295
Session*CR	1.62 (4.349, 86.971)	.075	.171
Session*CR (linear)	2.67 (1, 20)	.118	.118
Session*CR (quadratic)	2.24 (1, 20)	.101	.150
Session*SR*CR	1.22 (4.349, 86.971)	.057	.309
Session*SR*CR (linear)	1.85 (1, 20)	.085	.188
Session*SR*CR (quadratic)	.77 (1, 20)	.037	.391
SR	.406 (1, 20)	.020	.531
CR	.371 (1, 20)	.018	.549
SR*CR	.135 (1, 20)	.007	.717

Mixing Costs. The mixing costs are costs that are associated with having prepared both tasks within one block. To asses the costs the single-task RTs of the mix blocks (intermixed dual-task, manual and vocal single-task trials) were extracted that were not associated with a switch from either a dual-task trial or from a single-task trial of the other output modality (i.e. only single-task repetitions were extracted). Task switches have been shown to additionally slow RTs in comparison to a repetition of a task on consecutive trials (Rogers & Monsell, 1995) and are often labelled as local switching costs. Subsequently the single-task RTs of the single-task blocks were subtracted from the non switch single-task RTs of the mix blocks. This was done separately for the manual and the vocal task.

An ANOVA (see Table 4.5) with task (2) and session (8) as within and S-R (2) and C-R pairing (2) as between-subject factors revealed equivalent mixing costs for the vocal and the manual tasks. Mixing costs reduced with practice. Standard S-R pairing tasks produced lower mixing costs than the Non Standard SR pairing tasks. Standard C-R pairing tasks also resulted in smaller mixing costs than the Non Standard C-R pairing tasks. The S-R pairing effect was stronger for the manual than for the vocal task. Whereas the manual task showed an interaction of the S-R and C-R pairing factors where the S-R pairing effect was stronger for the C-R Non Standard compared to the Standard tasks, the vocal task showed equal S-R pairing effects for the Standard and Non Standard C-R pairing tasks.

Table 4.5. Summary of the ANOVA results on the mixing costs in RTs as a function of output modality, session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial *η2*	*p*
Session (linear)	47.60 (1, 20)	.704	<.001
Session (quadratic)	20.22 (1, 20)	.503	<.001
Session *SR	1.22 (2.63, 52.50)	.058	.309
Session *SR (linear)	1.46 (1, 20)	.068	.240
Session *SR (quadratic)	1.81 (1, 20)	.083	.194
Session*CR	.63 (2.63, 52.50)	.300	.580
Session*CR (linear)	.58 (1, 20)	.028	.455
Session*CR (quadratic)	.65 (1, 20)	.031	.431
Session*SR*CR	1.49 (2.63, 52.50)	.069	.232
Session*SR*CR (linear)	.03 (1, 20)	.001	.868
Session*SR*CR (quadratic)	3.59 (1, 20)	.152	.073
Output modality	.04 (1, 20)	.002	.836
Output modality *SR	26.12 (1, 20)	.566	<.001
Output modality *CR	.04 (1, 20)	.002	.840
Output modality *SR*CR	7.47 (1, 20)	.272	.013
Output modality *Session	.29 (1, 20)	.014	.839
Output modality *Session (linear)	.01 (1, 20)	<.001	.923
Output modality *Session (quadratic)	.45 (1, 20)	.022	.509
Output modality *Session *SR	.50 (2.63, 52.50)	.025	.690
Output modality *Session *SR (linear)	1.27 (1, 20)	.060	.273
Output modality *Session *SR (quadratic)	.15 (1, 20)	.008	.700
Output modality *Session*CR	.64 (2.63, 52.50)	.031	.598
Output modality *Session*CR (linear)	.89 (1, 20)	.043	.357
Output modality *Session*CR (quadratic)	.12 (1, 20)	.006	.738
Output modality *Session*SR*CR	1.63 (2.63, 52.50)	.075	.189
Output modality *Session*SR*CR (linear)	2.27 (1, 20)	.102	.148
Output modality *Session*SR*CR (quadratic)	1.48 (1, 20)	.069	.239
SR	9.64 (1, 20)	.325	.006
CR	21.51 (1, 20)	.518	<.001
SR*CR	1.38 (1, 20)	.065	.254

Manual mixing costs. Separate analyses on both, the manual and the vocal mixing task costs were conducted with session(8) as within-subject factor and S-R and C-R pairing as between-subject factors. The results confirmed the results of the over-all analysis. The manual mixing costs (Table 4.6) reduced with training. The C-R Non Standard tasks showed stronger mixing costs than the C-R Standard tasks. Non Standard S-R pairing tasks also exhibited greater mixing costs than the Standard S-R pairing tasks. The S-R pairing effect was more pronounced for the C-R Non Standard tasks than for the C-R Standard pairing tasks.

Table.4.6. Summary of the ANOVA results on the manual mixing costs in RTs as a function of session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	38.00 (1, 20)	.655	<.001
Session (quadratic)	9.48 (1, 20)	.322	.006
Session *SR	1.28 (2.528, 50.552)	.060	.291
Session *SR (linear)	3.50 (1, 20)	.149	.076
Session *SR (quadratic)	1.09 (1, 20)	.052	.309
Session*CR	.37 (2.528, 50.552)	.018	.745
Session*CR (linear)	<.01 (1, 20)	<.001	.971
Session*CR (quadratic)	.48 (1, 20)	.023	.497
Session*SR*CR	2.40 (2.528, 50.552)	.107	.089
Session*SR*CR (linear)	1.42 (1, 20)	.066	.247
Session*SR*CR (quadratic)	3.63 (1, 20)	.153	.071
SR	42.49 (1, 20)	.680	<.001
CR	20.31 (1, 20)	.504	<.001
SR*CR	9.18 (1, 20)	.315	.007

Vocal mixing costs. The vocal mixing costs reduced with training (see Table 4.7.). The S-R pairing factor showed no significant effect on the vocal mixing costs, whereas Standard C-R pairing tasks yielded smaller vocal mixing costs than the Non Standard C-R pairing tasks.

Table 4.7. Summary of the ANOVA results on the vocal mixing costs in RTs as a function of session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	25.04 (1, 20)	.556	<.001
Session (quadratic)	8.98 (1, 20)	.310	.007
Session *SR	.32 (3.362, 67.248)	.016	.835
Session *SR (linear)	.06 (1, 20)	.003	.805
Session *SR (quadratic)	.53 (1, 20)	.026	.475
Session*CR	1.00 (3.362, 67.248)	.047	.410
Session*CR (linear)	1.13 (1, 20)	.054	.300
Session*CR (quadratic)	.12 (1, 20)	.006	.737
Session*SR*CR	.45 (3.362, 67.248)	.022	.743
Session*SR*CR (linear)	.50 (1, 20)	.024	.489
Session*SR*CR (quadratic)	.19 (1, 20)	.009	.668
SR	.26 (1, 20)	.013	.616
CR	10.12 (1, 20)	.336	.005
SR*CR	.38 (1, 20)	.019	.544

Mixing costs on RTs for the last session. For the last session it was tested whether the mixing costs could be eliminated for each modality-pairing group. Table 4.8 shows the results together with the mean costs. Mixing cost of the last session were not eliminated for any group. Nevertheless the mixing costs for the C-R Standard groups were low, especially for Group 1 with the S-R and C-R Standard pairings.

Table. 4.8. Mean Mixing costs in RTs, Standard Deviations and T-test statistics on the mixing costs in RTs for session eight of each group.

Group	*M* (*SD*)	*T* (df)	*p*
1 (S-R Standard, C-R Standard)	18.79 (14.53)	3.17 (5)	.025
2 (S-R Non Standard, C-R Standard)	30.86 (25.83)	2.93 (5)	.033
3 (S-R Standard, C-R Non Standard)	50.35 (34.86)	3.54 (5)	.017
4 (S-R Non Standard, C-R Non Standard)	88.43 (31.30)	6.92 (5)	.001

Dual-task costs. Dual-task costs for each task were computed as the difference of the RTs in the non switch dual-task trials and the non switch single-task trials of the mix blocks of the same session. As already mentioned for the mixing costs switch trials are associated with higher RTs than repetition trials. Therefore, eliminating them from the single-task RTs of the mix blocks yields a more conservative baseline for the dual-task cost calculation within the present SPP. Switch costs for dual-task trials were not assumed to be as high as for single-task trials of the mix blocks but were also discarded to not overestimate costs and to treat both dependent measurements equally.

An overall ANOVA (see Table 4.9.) with task (2) and session (8) as within and S-R and C-R pairing as between-subject factors was conducted on the dual-task costs. Both tasks, the manual and the vocal had comparable dual-task costs of about 117 ms. Dual-task costs decreased with training. The S-R pairing factor had no influence on the dual-task costs. The C-R pairing effect comprised about 166 ms, whereby Standard C-R pairing tasks (34 ms) showed significantly lower dual-task costs than Non Standard C-R pairing tasks (200 ms).

Table 4.9. Summary of the ANOVA results on the dual-task costs in RTs as a function of output modality, session, S-R and C-R modality-pairing.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	26.24 (1, 20)	.567	<.001
Session (quadratic)	3.81 (1, 20)	.160	.065
Session *SR	.74 (2.458, 49.151)	.036	.506
Session *SR (linear)	.32 (1, 20)	.016	.576
Session *SR (quadratic)	.23 (1, 20)	.011	.637
Session*CR	1.16 (2.458, 49.151)	.055	.329
Session*CR (linear)	.48 (1, 20)	.024	.495
Session*CR (quadratic)	2.87 (1, 20)	.126	.106
Session*SR*CR	.83 (2.458, 49.151)	.040	.466
Session*SR*CR (linear)	.13 (1, 20)	.006	.725
Session*SR*CR (quadratic)	1.59 (1, 20)	.074	.221
Output modality	<.01 (1, 20)	<.001	.990
Output modality *SR	1.26 (1, 20)	.059	.276
Output modality *CR	1.50 (1, 20)	.070	.235
Output modality *SR*CR	.04 (1, 20)	.002	.840
Output modality *Session	1.03 (2.022, 40.435)	.049	.366
Output modality *Session (linear)	.54 (1, 20)	.026	.470
Output modality *Session (quadratic)	.08 (1, 20)	.004	.778
Output modality *Session *SR	2.16 (2.022, 40.435)	.097	.129
Output modality *Session *SR (linear)	3.72 (1, 20)	.157	.068
Output modality *Session *SR (quadratic)	.41 (1, 20)	.020	.529
Output modality *Session*CR	.83 (2.022, 40.435)	.040	.443
Output modality *Session*CR (linear)	.01 (1, 20)	.001	.916
Output modality *Session*CR (quadratic)	1.77 (1, 20)	.081	.198
Output modality *Session*SR*CR	.49 (2.022, 40.435)	.024	.618
Output modality *Session*SR*CR (linear)	<.01 (1, 20)	<.001	.992
Output modality *Session*SR*CR (quadratic)	1.09 (1, 20)	.052	.309
SR	2.05 (1, 20)	.093	.168
CR	34.60 (1, 20)	.634	<.001
SR*CR	1.83 (1, 20)	.084	.191

Dual-task costs on RTs for the last session. The dual-task costs of the last session were tested for modality pairings. The results for the ANOVA testing S-R and C-R modality-pairings on final dual-task costs are shown in Table 4.10. They mirror the results of the over-all analysis. The manual and the vocal tasks did not differ in dual-task costs at the end of practice. C-R Non Standard groups exhibited more costs than C-R Standard groups. The costs did not vary with S-R pairing. Figure 4.2 displays dual-task costs of the last session as a function of modality pairings.

Table 4.10. Summary of the ANOVA results on the dual-task costs in RTs of session eight as a function of output modality, S-R and C-R modality-pairing.

Effect	*F*(df)	partial η^2	*p*
Output modality	.31 (1, 20)	.015	.586
Output modality *SR	.01 (1, 20)	<.001	.921
Output modality *CR	.40 (1, 20)	.019	.536
Output modality *SR*CR	.03 (1, 20)	.001	.875
SR	2.65 (1, 20)	.117	.119
CR	35.81 (1, 20)	.642	<.001
SR*CR	2.64 (1, 20)	.117	.120

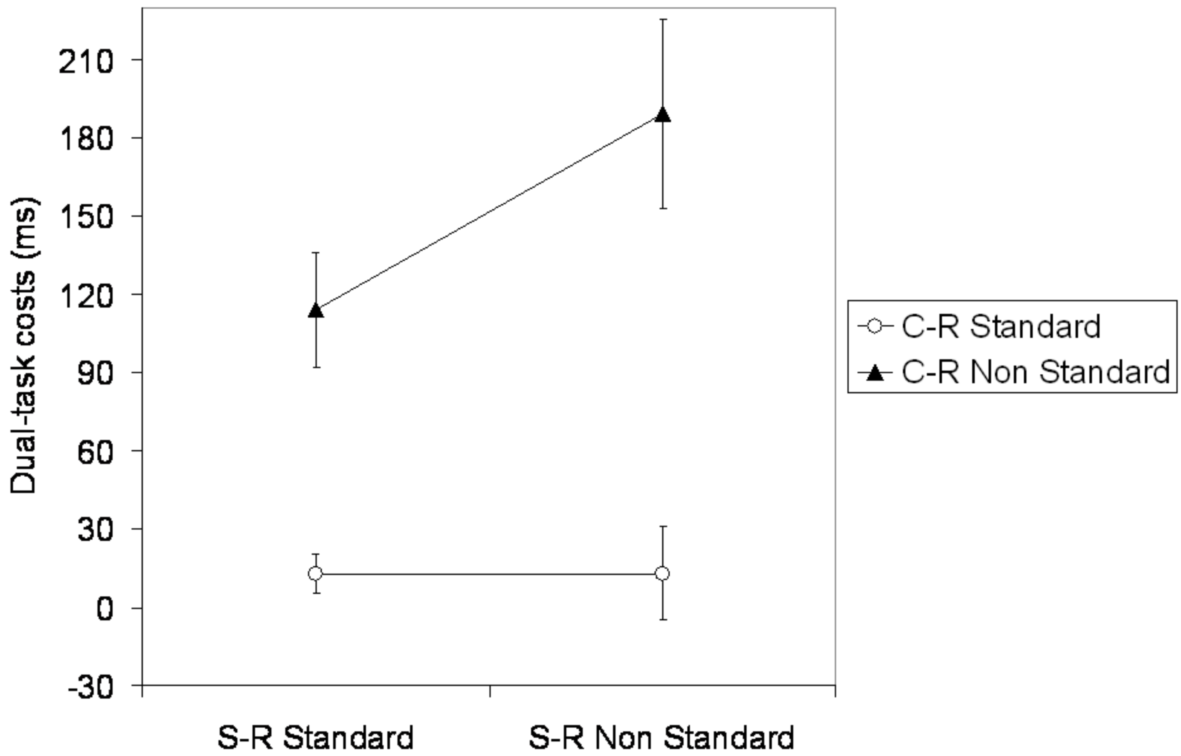

Figure 4.2 Dual-task costs in RTs of session eight as a function of S-R and C-R pairing effects. Error bars represent standard errors of the mean.

To test whether parallel processing was accomplished I conducted separate T-tests on the mean dual-task costs of the last session of each S-R and C-R group. The T-test results were clear cut. They are summarized in Table 4.11. The mean dual-task costs of both C-R Standard groups were only minor, and indistinguishable from zero. The C-R Non Standard groups yielded large mean dual-task costs at the end of practice that were significantly higher than zero.

Table. 4.11. Mean RTs, Standard Deviations and T-test statistics on the residual dual-task costs in RTs of session eight separately for each group of Experiment 3.

Group	*M* (*SD*)	*T* (df)	*p*
1 (S-R Standard, C-R Standard)	12.88 (18.73)	1.68 (5)	.153
2 (S-R Non Standard, C-R Standard)	12.93 (43.75)	.72 (5)	.501
3 (S-R Standard, C-R Non Standard)	114.02 (53.21)	5.25 (5)	.003
4 (S-R Non Standard, C-R Non Standard)	189.44 (88.43)	5.25 (5)	.003

Accuracy. As for the RT data a task (manual, vocal) x session (8) x S-R pairing (2) x C-R pairing (2) ANOVA was conducted on the PEs. This was done separately for the single-task PEs, mixing costs in PEs and dual-task costs in PEs. In the case of significant interactions with the task factor separate analysis were conducted for each task. The detailed description of the ANOVA results was moved to the Appendix B.

Overall, there were no effects of S-R or C-R pairing or their interaction for the analysis of the single-task PEs, the mixing costs in errors. For the ANOVA on the dual-task costs in errors there were significant modality-pairing effects that allways pointed into the same direction as their effects on dual-task costs in RTs, i.e. Non Standard tasks produced higher error rates than Standard tasks. Hence, there was no speed-accuracy trade-off of the reported effects on the RT data and the error data that could have compromised the interpretation of the RT data.

Mixing costs in PEs for the last session. Separate T-tests (see Table 4.12) on the mixing costs in errors for the last session revealed negative values for the S-R Non Standard, C-R Standard group (2) that just reached the level of significance. Negative values reflect mixing benefits rather than costs. Hence, there was a trend for a speed-accuracy trade-off between the mixing costs in RT and PE for this group. For the other groups the mixing costs in PEs were not significant at the end of practice.

Table. 4.12. Mean PEs, Standard Deviations and T-test statistics on the mixing costs in PEs of session eight for each group in Experiment 3.

Group	*M* (*SD*)	*T* (df)	*p*
1 (S-R Standard, C-R Standard)	-1.36 (2.03)	-1.64 (5)	.161
2 (S-R Non Standard, C-R Standard)	-1.62 (1.60)	-2.47 (5)	.057
3 (S-R Standard, C-R Non Standard)	.22 (3.54)	.15 (5)	.886
4 (S-R Non Standard, C-R Non Standard)	-.43 (2.07)	-.52 (5)	.628

Dual-task costs in PEs for the last session. As for the dual- task costs in RTs it was tested whether dual-task costs in errors were eliminated for each S-R and C-R group at the end of practice. Table 4.13. shows the statistics of the separate T-tests for the modality-pairing groups. Averaged over both tasks the S-R Non Standard- C-R Standard group (2) exhibited small but significant dual-task costs in errors at the end of training. The other three groups did not posses significant dual- task costs in errors.

Table 4.13. Mean RTs, Standard Deviations and T-test statistics on the residual dual-task costs in PEs of session eight for each group in Experiment 3.

Group	*M* (*SD*)	*T* (df)	*p*
1 (S-R Standard, C-R Standard)	1.19 (1.29)	2.25 (5)	.074
2 (S-R Non Standard, C-R Standard)	.94 (.82)	2.80 (5)	.038
3 (S-R Standard, C-R Non Standard)	.19 (3.51)	.13 (5)	.901
4 (S-R Non Standard, C-R Non Standard)	2.19 (2.49)	2.16 (5)	.083

4.3. Discussion

Experiment 3 tested whether representational overlap across tasks can explain modality-pairing effect on dual-task costs via content-based crosstalk. Representational overlap was varied across groups by manipulating the nature of S-R and C-R modality-pairings being either Standard or Non Standard for both tasks. The results showed that both S-R and C-R pairings affected dual-task costs stronger than it has been predicted according to their effects on single-task performance.

The C-R pairing had strongest effect on dual-task costs. Overall dual-task costs were about 166 ms higher for the C-R Non Standard than for the C-R Standard tasks. The C-R pairing effect on single-task RTs was, however, smaller. There was only an effect on manual but not on vocal single-task RTs. Manual single-task RTs increased for Non Standard C-R pairings about 100 ms compared to C-R Standard pairings. This difference in the C-R pairing effects on single-task RTs and dual-task costs was significant, $F(1,20)= 42.74$, $p<.001$, partial $\eta^2= .681$.

The S-R pairing effect on dual-task costs was, however, not significant. But S-R pairings produced an inverse effect on manual single-task RTs that was not observable for the vocal task. Manual single RTs were about 100 ms faster for Non Standard than for the Standard S-R modality-pairings. Hence, the Non Standard S-R modality-pairings produced higher dual-task costs than it would have been predicted on their single-task performance. The difference in the S-R pairing effects on the single task RTs compared to the dual-task costs was significant, $F(1,20)= 19.22$, $p<.001$, partial $\eta^2= .490$.

The inverse S-R pairing effect on the manual single-task RTs can be explained by the fact that the S-R pairing factor in the manual task was confounded with the number of choice alternatives. The manual tasks with Standard S-R pairs always entailed a three-choice reaction and the Non Standard manual S-R pairs a two-choice reaction. The number of S-R alternatives is known to influence central processing times with fewer alternatives producing shorter central processing and hence shorter overall RTs. Therefore, the confounding explains the inverse S-R pairing effect on manual single-task RTs.

Content-based crosstalk and quality of processing

A further important observation was that dual-task costs not only were smaller for C-R Standard compared to the Non Standard pairing groups but could even be eliminated at the end of practice (although small but significant residual costs in PEs were observed for Group 2). The vanished dual-task costs for the C-R Standard groups are interpreted as parallel processing (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001). According to the content-based crosstalk assumption the low representational overlap between two tasks for the C-R Standard groups produced low potential for crosstalk. Therefore, the binding processes defining which stimulus code belongs to which response code can largely be applied independently. With practice a parallel processing schedule could be established for the two groups. There are alternative explanations trying to keep a serial processing interpretation for the C-R Standard groups, which are less likely but nevertheless discussed below.

For the C-R Non Standard groups costs remained significant after practice. What do the dual-task costs for the C-R Non Standard groups tell about the quality of their processing? Was serial processing still active after practice? For the groups the representational overlap due to the C-R Non Standard pairings is assumed to produce strong crosstalk. When crosstalk happens it has to be undone to cancel out potential errors or it has to be prevented at the outset. Thereby, the first possibility is associated with crosstalk only, i.e. parallel processing despite crosstalk. The second possibility is associated with a functional bottleneck, i.e. serial processing due to crosstalk. Both would be in accordance with the present results. The crosstalk account does not favour one interpretation. However, the present data cannot answer this question. It was tried to answer in Experiment 4 where the groups were transferred to a PRP paradigm with their respective two tasks.

Present results in light of EPIC

Prominent dual-task theories as the EPIC account and the traditional view of the central bottleneck theory (Pashler, 1994a) have strong problems to account for the results. Within the EPIC framework Meyer and Kieras (Meyer & Kieras, 1997a) formulated the preconditions for parallel processing. These preconditions were fulfilled with respect to all groups of Experiment 3. Between the two tasks the sensory and response modalities did not overlap (in fact, even the central modalities did not overlap between tasks although this is not critical to the EPIC theory). The opportunity to practice the two tasks in combination was given for eight sessions, while no task was prioritizes through instruction or experimental setup and incentives were given for fast responding. This should have enabled the members of all groups to process their two tasks in parallel. For this reason, the EPIC model predicted not only minimal dual-task costs for each group but also equal costs across groups, i.e. no effect of modality pairings. Therefore, the predictions of the EPIC account are not in line with present results. With the postulation of different task scheduling strategies for the C-R Standard and the C-R Non Standard groups, i.e. a daring vs. a cautious strategy the EPIC account could be saved. Such a postulation, however, would cancel out its postulated preconditions for parallel processing. Even postulating different task scheduling strategies due to the differential single-task performances across the groups could not explain the stronger differences in the dual-task costs across the groups.

Present results in light of the bottleneck and the latent bottleneck account

Also for the traditional formulation of the bottleneck theory (Pashler, 1994a) problems arise out of the differential effects of S-R and C-R modality-pairings on dual-task costs and single-task RTs to account for the present data. The bottleneck account postulates strict serial processing of central stages of two tasks. Thereby, dual-task costs should depend on central processing duration of the task that is processed first. Consequently, factors influencing central duration of Task 1 should full size propagate onto dual-task costs. According to that idea the effects of S-R and C-R pairings on single-task RTs should be taken as a predictor for their effects on dual-task costs. However, differences in dual-task cost between C-R pairing groups cannot originate by differences in single-task RTs since there was no C-R pairing effect of 166 ms on either vocal or manual single-task RTs. The C-R pairing effect on manual single-task RT amounted only about 100 ms. Hence, the observed C-R pairing effect on dual-task costs is higher than predicted by assuming the manual task being processed first. At the same time, if one assumes that the manual task was always processed first also the inverse S-R pairing effect observed for the manual single-task RTs should have been visible in dual-task costs. Additionally, this was not the case. Furthermore, the scenario that the manual task was always processed first would imply that dual-task costs were only found on the vocal task. However, equal dual-task costs for the vocal and the manual task were observed.

Another result that is not in accordance with the general scenario of the processing bottleneck is that the dual-task costs could be eliminated for the two C-R Standard pairing groups. As the bottleneck theory assumes that two tasks cannot be processed in parallel, costs should always emerge. However, the theory explains minimal dual-task interference with the assumption of a latent bottleneck (Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). The term describes a situation where the central processing stage of one task takes no more time than the difference between the sensory components of both tasks. This makes it possible that central stages of the two tasks never come into conflict since central processing of Task 1 is always already finished when Task 2 is ready to enter the bottleneck. Therefore dual-task costs do not appear. Factors reducing central stage processing promote the latent bottleneck. In the present design practice is one factor that could have facilitated a latent bottleneck (Ruthruff, Johnston, & Van Selst, 2001). Thus, assuming a latent bottleneck the vanished dual-task costs after practice for the C-R Standard pairing groups in the present design would be in accordance with the bottleneck theory. Is it possible that the bottleneck was bypassed for the C-R Standard groups? On the basis of the present results the latent bottleneck account cannot be completely ruled out but there are several aspects that make it rather unlikely. As the latent bottleneck depends on a) short central processing stages of at least one task and b) on the differences in stimulus encoding stages of both tasks, there are two scenarios to be discussed that could create a latent bottleneck for both C-R compatible groups: the "spatial task first" scenario and the "auditory task first" scenario. They are discussed in the following.

At first I look at the "spatial task first" scenario. It is outlined in Figure 4.3. This scenario is motivated by the single-task characteristic that differentiates the C-R Standard pairing groups from the Non Standard groups: shorter manual single-task RTs. This entails that the spatial central processing stages are shorter for the Standard than for the Non Standard C-R pairing groups. The "spatial task first" scenario assumes that the spatial (and at the same time also manual) tasks of Group 1 and 2, always enter the bottleneck first (see Figure 4.3, Group 1 and Group 2 version a). Moreover, the central plus sensory stages of the spatial-manual tasks had to be shorter or at maximum equally long as the sensory stage of verbal-vocal task. In this case, the central stages of the spatial-manual and the verbal-vocal tasks do not come into conflict for both C-R Standard groups. To this end, the sensory stage of verbal-vocal task should always be shorter than sensory stage of spatial-manual task. But the modality of sensory stages for the verbal-vocal tasks differed between the two C-R Standard groups. This entails, however a counterintuitive result. According to the spatial task first scenario for Group 1 the visual encoding of Task 1 should have been slower than auditory encoding stage of Task 2.

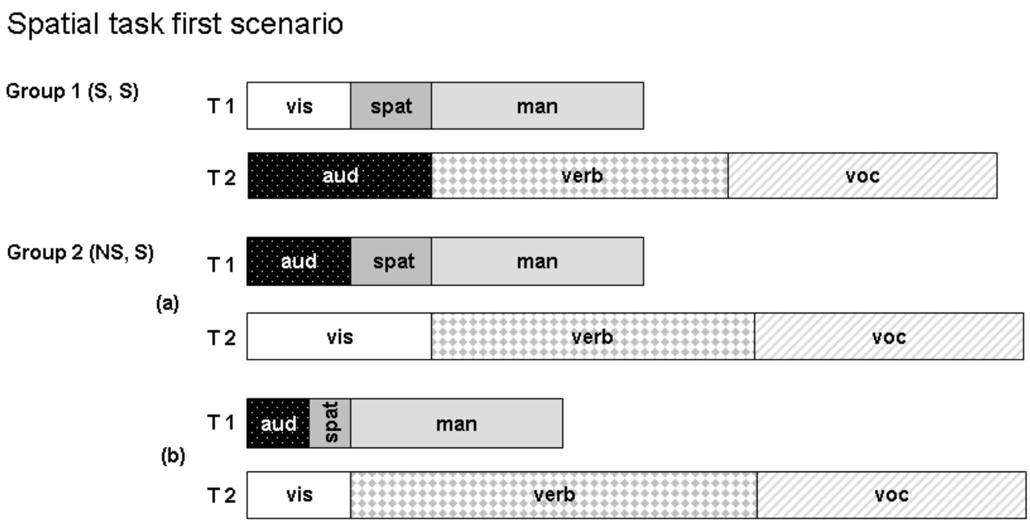

Figure.4.3. Stage diagrams of the „spatial task first" scenario postulating a latent bottleneck for the C-R Standard groups. Task processing is decomposed into three stages denoted by its modality. The first stage of each task is the stimulus encoding stage, which either can be visual (vis) or auditory (aud) in nature. The second stage is the central processing stage, which either can be spatial (spat) or verbal (verb). The third stage is the response execution stage, which either can be vocal (voc) or manual (man). For both groups the spatial task always enters the bottleneck first (T1) followed by the verbal task (T2). The stimulus encoding stage plus the central processing stage of Task 1 equals the duration of the stimulus encoding stage of Task 2. Thereby, the central processing stages of the two tasks never occur at the same time. For Group 2 two different variants for the scenario are given. Variant a) and b) fulfil both the assumptions of the "spatial task first" scenario. They differ at first with respect to the overall length of the auditory-spatial-manual task due to shorter auditory encoding and spatial processing stages. This difference entails that the visual encoding stage for Task 2 of Group 2 can be as long as for Task 2 of Group 1.

For Group 2, however, the relation between the stimulus encoding stages has to be reversed to fulfil the conditions for the spatial task first scenario. The auditory encoding of Task 1 should have been slower than visual encoding stage of Task 2. When accounting for the fact that the manual single-task RT for Group 2 is shorter than for Group 1 (S-R pairing effect on manual single-task RTs, two choice task for Group 2 in comparison to three choice task for Group 1), the central stage duration for the spatial task of Group 2 has to be shortened compared to the one of Group 1. This causes the fact that the duration of the visual encoding stage of the two groups does not have to differ between them to produce a latent bottleneck for both C-R Standard groups. Nevertheless, the duration of the auditory encoding stage still has to vary dramatically between the groups. This adaptation for Group 2 is displayed in the lower part of Figure 4.3 (Group 2- version (b).

In general this "spatial task first" scenario is appealing because it uses the single-task RT characteristic that separates C-R Standard from C-R Non Standard groups (short central duration times of the C-R Standard manual tasks) to explain group differences in dual-task costs. Furthermore, the timing seems plausible for each group alone. However, the plausibility of a latent bottleneck for both groups is reduced assuming opposite duration relations of the visual and the vocal perceptual encoding stages between the two groups.

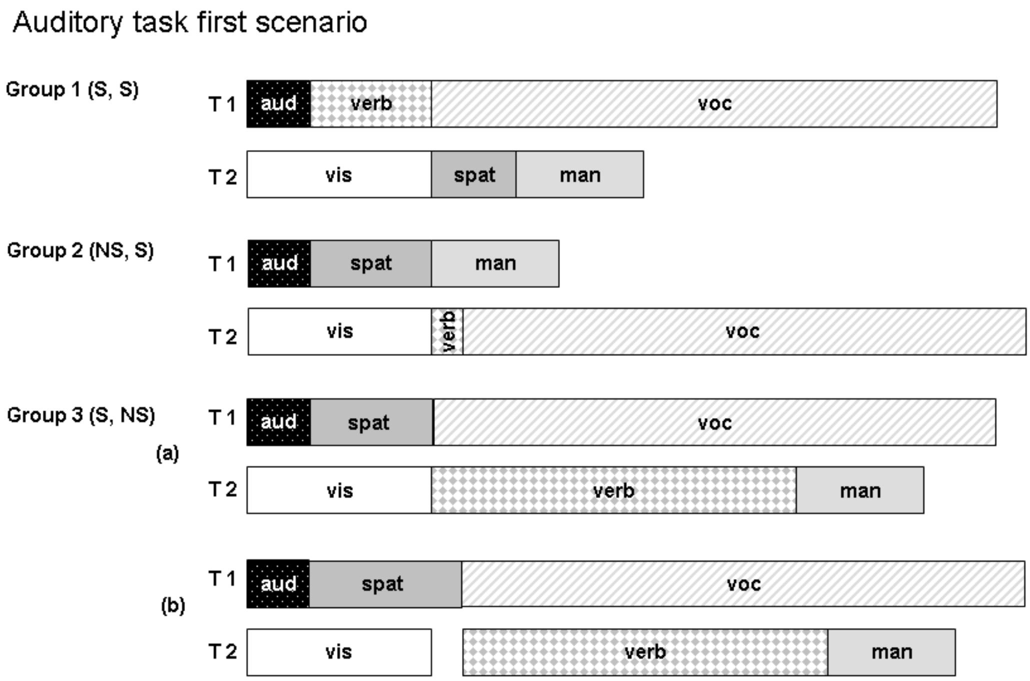

Figure.4.4. Stage diagrams of the „auditory task first“ scenario postulating a latent bottleneck for the Group 1, 2 and 3. Task processing is decomposed into three stages denoted by its modality. The first stage of each task is the stimulus encoding stage, which either can be visual (vis) or auditory (aud) in nature. The second stage is the central processing stage, which either can be spatial (spat) or verbal (verb). The third stage is the response execution stage, which either can be vocal (voc) or manual (man). For all groups the auditory task always enters the bottleneck first (T1) followed by the visual task (T2). The stimulus encoding stage plus the central processing stage of Task 1 equals the duration of the stimulus encoding stage of Task 2. Thereby, the central processing stages of the two tasks never occur at the same time. For Group 3 two different variants for the scenario are given. Variant a) fulfils the assumptions of alatent bottleneck scenario. Variant b) does not. Variant b) takes the slightly higher RTs for the vocal Task 1 of Group 3 compared to the vocal Task 1 of Group 1 into account, which could lead to the re-emergence of the latent bottleneck in some or all trials for Group 3.

Another latent bottleneck scenario for the C-R Standard groups is the "auditory task first" scenario. It assumes constant encoding stage durations for the auditory and the visual modality across the two groups with the auditory stimulus encoding stage being shorter than the visual (see Figure 4.4, Group 1 and 2). It is known from neuropsychological studies that processing in the auditory modality is faster than in the visual modality (Bruce, Desimone, & Gross, 1981; Nowak, Munk, Girard, & Bullier, 1995; Recanzone, Guard, & Phan, 2000). Hence, the tasks with the auditory input modality could have entered the bottleneck always first (i.e the verbal for Group1 and the spatial for Group 2). To result in a latent bottleneck for Group 1 the overall longer verbal-vocal task is always processed first and for Group 2 the shorter spatial-manual task. This scenario seems not implausible, but causes other questions. It cannot be exclusively applied to the C-R Standard groups. With the assumptions of the "auditory task first" scenario one has to ask why Group 1 but not Group 3 exhibited a latent bottleneck. The lower part of Figure 4.4 shows the application to Group 3 (Group 3- version a). The Group 3 differs from Group 1 in the C-R, not the S-R pairings of both tasks. The Group 3 constitutes as Group 1 of an auditory-vocal and a visual-manual task (S-R pairings). Hence, one has to assume similar stimulus encoding and response stage durations for these groups. Differences between single-task RTs of the two groups can only be due to the central stage durations (as C-R pairing is assumed to affect central stage durations). But the central processing stages of the vocal tasks cannot dramatically differ between Group 1 and 3 given that for the last session the vocal single-task RTs between Group 1 (*M*: 448 ms, *SD*: 91.89) and Group 3 (*M*: 470 ms, *SD*: 70.84) were not significantly different, $t(10)=-.48$, $p=.640$ (like overall C-R pairing had no effect on the vocal single RTs). Even taking single mixing tasks as a single-task baseline (i.e., single-task RTs of the mix blocks), no difference between the Group 1 (*M*: 485 ms, *SD*: 80.17) and Group 3 (*M*: 533 ms, *SD*: 100.22) was observable, $t(10)=-.980$, $p=.385$. For Group 1 the central processing stage of the verbal-vocal task is short enough to leave the bottleneck when the visual encoding stage of the second task is ready to start with central processing. Therefore, the auditory plus central stage of the spatial-vocal task of Group 3 should also be as long as the visual encoding stage of the visual-spatial-manual task. Hence, according to the "auditory task first" scenario Group 3 should also have the potential to exhibit a latent bottleneck. Even when assuming that the non significant difference in the vocal single RTs of 22 ms (or 48 ms for the vocal mixing RT) between Group 1 and Group 3 resulted on some trials in a longer central stage duration of Group 3 compared to Group 1 the bottleneck should only become apparent on these trials (see Figure 4.4 Group 3- version b). However, the dual-task costs on the manual task of Group 3 should be lower. They should not equal to the observed 118 ms. The increase in costs from Group 1 to 3 for the manual task should not be higher than the increase in single-task RT from Group 1 to 3, i.e. 22 ms. Assuming only a frequent latent bottleneck for Group 3 the costs for manual task should even be smaller than this difference. Taken together, the assumption of a latent bottleneck as an explanation of the minimal dual-task costs for the C-R Standard groups is not very plausible as both scenarios showed.

Automatization

Another idea explaining vanished dual-task costs within the bottleneck framework is the concept of automatization. Due to extensive practice central processing is assumed not to be limited in capacity. Hence, the bottleneck can be bypassed through the automatization of at least one task. When applied to the observed minimal dual-task costs the question raises why not all groups showed automatization as they all practice their task for the same amount of trials? Considering automatization as a gradual process the time for automatization depends on central duration of the tasks. In this sense the low costs of the C-R Standard modality-pairing groups were due to an automatized manual task. However, Oberauer & Kliegl (2004) showed that automatization alone is not sufficient to eliminate dual-task costs. In their Experiment 2, Oberauer & Kliegl practiced one group of participants on the dual-task combination of numerical and spatial memory updating task. Another group trained on a single-task condition of these tasks for the same overall amount of practice. Only the group practicing the dual-task condition showed substantially diminished dual-task costs, ruling out the automatization account for explaining vanished dual-task costs after practice.

Baseline problems

One way to question the interpretation of parallel processing for the C-R Standard groups is to challenge the way dual-task costs were computed in the present experiment. Dual-task costs were computed as the difference of dual-task RTs and single-task RTs of the mix blocks. The single-task RTs of the mix blocks, however, were still increased compared to single-task RTs of the single-task blocks. This resulted in significant mixing costs for all groups even at the end of practice. Hence, this procedure of computing dual-task costs could have underestimated dual-task costs. Calculating dual-task costs as the difference of dual-task RTs and single-task RTs (out of single-task blocks) causes non zero costs for the C-R Standard groups and hence challenges the interpretation of parallel processing for these two groups. However, at the same time this method would even increase the difference of the modality-pairing effects on dual-task costs versus single-task RTs. Hence, using the more conservative single-task baseline cannot save the central bottleneck (Pashler, 1994a) as an explanation for the present data. Nevertheless, to clearly demonstrate that dual-task costs could be eliminated and parallel processing was reached for the C-R Standard groups, both groups were transferred to a PRP paradigm. In the PRP paradigm there is no methodological uncertainty about the baseline for calculating dual-task costs. The calculation of dual-task costs is defined by subtracting Task 2 RTs at the shortest SOA minus Task 2 RTs at the longest SOA. The transfer of the dual-task groups that is described in Experiment 4 will show that even using a different paradigm parallel processing can be demonstrated for the C-R Standard pairing groups.

Present results in light of the multiple resource theory

A dual-task theory that claims to predict modality pairings on dual-task costs is the multiple resource theory of Wickens (Wickens, 1980). As mentioned in a note in the introductory part the S-C-R modality-pairing taxonomy used for the present groups is adopted by the multiple resource theory. The multiple resource theory is a content dependent theory, i.e. not only the central processing duration but the content of the information processing stages plays a role especially for dual-task performance. According to the theory different information processing stages draw on distinct pools of resources. Wickens postulates resource pools for the processing stages of perceptual encoding (visual vs. auditory), central processing (spatial vs. verbal) and response executing (manual vs. vocal). A simple but not trivial inference that can be drawn includes that a dual-task combination with two verbal tasks causes more interference than a verbal and a spatial task. A further assumption of Wickens et al. (1983) holds interactions between the pools of resources, which he refers to as stimulus-central-response compatibility (S-C-R compatibility). Thereby the visual-spatial-manual and the auditory-verbal-vocal resource combinations are the most compatible. The S-C-R compatibility is claimed not only to influence single but also dual-task performance (Wickens, Sandry, & Vidulich, 1983). With this postulation the multiple resource account seems to be a viable framework to explain the present modality-pairing effects. However, Wickens does not explicitly formulate the underlying mechanism for this postulated compatibility. He motivates the argument by the description of the observed effects (Wickens, Sandry, & Vidulich, 1983). Merely out of the resource sharing mechanism, it does not become obvious why a highly S-C-R compatible task should be processed faster than a low S-C-R compatible task. Likewise, ensuring that in a dual-task situation two tasks do not share resources at all, as it was implemented for the present groups, it remains unclear why a combination of two resource compatible tasks should further reduce dual-task interference. In fact, Wickens did not test S-C-R compatibility effects on dual-task performance independently from resource sharing effects. Accepting the S-C-R compatibility concept within the multiple resource account by assuming that certain modality resource pools have something in common softens the boundaries of the concept resource. Therefore although the theory predicts different dual-task costs for different modality-pairing combinations, there is no mechanism given to explain the effect that would be in accordance with the resource idea. Therefore, it is not clear why not all groups showed equal low dual-task costs in the present experiment. For non of the groups there was overlap in sensory, central or response modalities between the tasks. Above all, Wickens theory is not clear in predicting differential effects of S-R and C-R pairings on dual-task costs and delivering a causing mechanism. The only prediction that can be drawn from Wickens is that next to the most compatible S-C-R combinations as implemented for Group 1 the costs increase for the other groups since modality pairings are not perfectly compatible. However, why Group 2 yielded a lesser increase in costs relative to its single-task performance than Groups 3 and 4 the resource sharing account is not explained apriori. Therefore, although the account claims to explain S-C-R effects on dual-task costs its explanatory power for the present results is rather low.

Conclusion

Taken together the results cannot be explained by the present dual-task theories assuming an amodal response selection stage that does not depend on the specific representations of the tasks to be processed. In addition, existing content dependent theories are not able to satisfactorily account for the observed modality pairings on dual-task costs effects. In contrast, the modality-pairing effects fully match the predictions assuming representational overlap due to common coding as the basis for modality-pairing effects. Representational overlap between stimulus and response across tasks produces content-based crosstalk. The present results moreover suggest that with practice for low crosstalk groups parallel processing can be reached. There is a small loophole for dual-task theories challenging parallel processing of two sensorimotor tasks. The vanished dual-task costs for the C-R Standard pairing groups were possibly deflated due to a less conservative single-task baseline that was used to calculate the costs. For this reason the groups with their respective two tasks were transferred to a PRP paradigm in the following experiment. The PRP paradigm uses a well established baseline to unequivocally test the C-R Standard groups for dual-task costs. Likewise, the two C-R Non Standard groups were transferred to a PRP paradigm in the subsequent Experiment 4. It was checked whether dual-task interference was only due to crosstalk or whether an additional bottleneck was apparent for these groups.

5. Experiment 4- Dual-task processing of S-R and C-R modality-pairing groups after practice within a PRP paradigm

In Experiment 3 S-R and C-R modality-pairings were found to influence dual-task costs stronger than single-task performance. This was attributed to crosstalk between tasks in the dual-task situation for the Non Standard S-R and C-R modality-pairings. Crosstalk was apparent due to the representational overlap across these tasks. The present Experiment 4 transfers the different S-R and C-R pairing groups that already had practiced their respective two tasks within the SPP in Experiment 3 to a PRP paradigm. The actual question is whether processing of two tasks was still serial after practice for these groups.

Practice in Experiment 3 reduced dual-task costs of all modality-pairing groups. Generally, a decrease in costs with practice can be attributed to a qualitative or a quantitative change in performance, whereby the former is associated with a switch from serial to parallel processing and the latter with the mere reduction of processing stage durations. However, reduction in costs reached different levels for the groups resulting in non significant dual-task costs for Standard C-R pairing groups and significant costs of about 170 ms for C-R Non Standard groups.

For the C-R Non Standard groups the present experiment should clarify whether crosstalk was the only source of dual-task interference or whether in addition to the crosstalk a bottleneck was active. Generally, postulating crosstalk being active for the C-R Non Standard groups implies interactions between the representations of the two tasks at central level. This parallelism would at first sight contradict the assumption of serial central processes never occurring at the same time as postulated in the bottleneck account. With an account of Hommel (1998a) the two sources of dual-task interference can be brought together. Hommel proposed that two processes drive the central S-R translation: activation and selection. Activation can take place in parallel for the two tasks and selection has to occur serially. Hommel (1998a) found that using two tasks with representational overlap across tasks (e.g., R1-R2 code overlap of Hommel's Exp. 1) RTs of Task 1 at short SOA being shorter when they were compatible with Task 2 responses compared to trials were they were incompatible. Hommel referred to this finding as the backward- compatibility effect. Additionally, he found a typical PRP effect on Task 2 RT indicating a bottleneck delay at short SOA. At first sight, the two effects, the backward compatibility effect and the PRP effect, contradict each other. The bottleneck account assumes that at short SOA the response to stimulus of Task 2 is not available since it passed through the bottleneck. Task 1 central processing, however, occupies the bottleneck. Hence, at short SOA the response of Task 2 could not have been available and consequently could not have influenced response selection of Task 1. Nevertheless, Hommel found the backward-compatibility effect at short SOA. He interpreted the backward-compatibility effect as a sign of fast-acting response activation operating in parallel for the two tasks. After the response activation the selection starts, which is, however, done serially in most cases.

Schubert, Fischer and Stelzel (Schubert, Fischer, & Stelzel, 2008) could show, that the pre activation of Task 2 is completely reset before it enters the bottleneck stage. To show this they used a PRP paradigm with an additional visual subliminal prime always presented shortly before the stimulus of Task 2. With the prime they could vary response activation of Task 2 independently from Task 1 characteristics. The prime could either be congruent or incongruent with the spatial stimulus information of Task 2. At short SOA this prime did not influence the amount of the PRP effect on Task 2 when there was no representational overlap across the two tasks (R1-R2 spatial compatibility). However, a model that assumes a complete bypass of the pre-activation of Task 2 would predict an effect of the congruence between prime and stimulus on the amount of the PRP effect. When there was representational overlap between Task 1 and 2 the prime influenced RT of Task 2 at short SOA. In this case RT of Task 2 was faster when the prime was congruent than when it was incongruent with Task 2 stimulus. The authors, however, don't assume a direct influence of the pre-activation of Task 2 due to the prime on the duration of its response selection stage. They assume an indirect congruency effect of the prime on RT2 via Task 1. Due to the representational overlap between Task 1 and 2 crosstalk happens during their activation stages at short SOA. This crosstalk increases the duration of the activation stage for Task 1 and 2 in the case of incongruent compared to congruent trials. Consequently Task 1 response selection stage started later when crosstalk increased the duration of its activation stage. Likewise Task 2 response selection stage has to wait longer for the finish of the response selection of Task 1. Thus, pre-bottleneck effects on Task 1 activation due to crosstalk fully propagate onto Task 2 at short SOAs. According to this prediction the authors found, the congruence effects on Task 2 at short SOA paralleled those on RT1. Moreover, the authors could show that the accumulated activation of Task 2 does not pass through the bottleneck but is erased after the end of the response selection of Task 1. It therefore does not directly influence the duration of the response selection stage for Task 2. Using two short SOAs with the prime always presented 85 ms before the stimulus of Task 2 the congruency effect on the PRP effect for Task 2 decreases from the shortest to the longer (medium) SOA. Though, the congruency effect on Task 2 PRP effect should increase from the shortest to the longer SOA when assuming that pre-activation of Task 2 was completely forwarded, i.e. directly influenced its response selection stage. This should happen because in the shortest SOA condition the induced delay in Task 2 is longer than in the medium SOA condition. Hence, the pre-activation of Task 2 due to the prime at the shortest SOA condition has more time to decrease than at the medium SOA. The authors explained the observed decreasing congruency effect on Task 2 PRP effect with the reduced temporal overlap of their activation stages. The time for crosstalk between the response activation stages of Task 1 and 2 is reduced from the shortest to the medium SOA. Hence, the amount of the congruency effect on Task 2 RT should be lower than for the shortest SOA where both activation stages overlap more. According to the results of Hommel (1998a) and Schubert et al. (Schubert, Fischer, & Stelzel, 2008) possibly both sources of interference, crosstalk and the bottleneck, have contributed to dual-task costs found for the C-R Non Standard groups.

In contrast the results of Hazeltine, Ruthruff and Remington (Hazeltine, Ruthruff, & Remington, 2006) and Hazeltine and Ruthruff (Hazeltine & Ruthruff, 2006) show that dual-task costs can be apparent without the operation of a response selection bottleneck. The difference to the former studies showing crosstalk with a bottleneck (Hommel, 1998a; Koch, 2009; Schubert, Fischer, & Stelzel, 2008) was that practice played a dominant role in Hazeltine et al. and Hazeltine an Ruthruff. In two successive studies the authors combined an SPP and a PRP paradigm and examined the influence of S-R modality-pairings on dual-task costs. In the SPP study of Hazeltine, Ruthruff and Remington (2006) two S-R modality-pairing groups reduced their dual-task costs during practice for a whole of 16 sessions. The groups differed in costs at the end of practice. The easy Standard modality-pairing group exhibited costs of about 30 ms and the Non Standard group of about 100 ms. This difference could not simply be attributed to their single-task differences. A third Standard S-R modality-pairing group (hard Standard group), which worked on a more difficult vocal task (but the same manual task as the easy Standard S-R group) produced equal single-task RTs as the Non Standard S-R mapping group but showed equal dual-task costs as the easy Standard S-R mapping group. However, dual-task costs remained significant after practice for all S-R pairing groups. Transferring the easy Standard and the Non Standard S-R pairing group to a PRP paradigm in the subsequent experiment Ruthruff, Hazeltine and Remington (Ruthruff, Hazeltine, & Remington, 2006) found no sign of a response selection bottleneck being the origin of the residual dual-task costs. For either group and in either task order any PRP effect on Task 2 was apparent. Moreover, the correlations between Task 1 and 2 did not increase for the short compared to the long SOAs, as would be predicted by the central bottleneck theory. The authors concluded that the bottleneck was eliminated with practice for the Standard as well as for the Non Standard modality-pairing group. Speculating on the nature of residual dual-task costs in the SPP the authors supposed that it is "natural to bind visual stimuli with manual responses. The opposite bindings (auditory stimuli to manual responses or visual stimuli to vocal responses) would need to fight this natural tendency. (…) [In] a dual-task condition (…) the stimulus categories would tend to bind with the response categories for the wrong task. (Ruthruff, Hazeltine, & Remington, 2006, p. 502)". This is what in Experiment 3 and 4 of the present thesis is denoted as crosstalk due to representational overlap. The result of the studies (Hazeltine, Ruthruff, & Remington, 2006; Ruthruff, Hazeltine, & Remington, 2006) showed that even when the bottleneck is eliminated with practice, residual dual-task costs due to other factors can be apparent. Thus, practice could also have eliminated the bottleneck for the C-R Non Standard groups in Experiment 3. In this case the residual costs for the C-R Non Standard groups would only be due to crosstalk. The present PRP experiment will test whether the observed dual-task interference for the C-R Non Standard groups will be in accordance with crosstalk plus bottleneck or just crosstalk.

In the PRP paradigm the manual and the vocal tasks practiced in Experiment 3 are not longer presented simultaneously. They are shifted in time against each other by a variable SOA. Thereby one task is presented first, referring to as Task 1, and the other second, i.e. Task 2. Hence, there are two possible orders in the present experiment: vocal task as Task 1 or the manual task as Task 1. For both orders it can be tested whether in addition to the crosstalk a bottleneck was present. Irrespective of crosstalk that is assumed for the C-R Non Standard groups, an additional bottleneck should manifest in two characteristics. The first is the PRP effect on Task 2 in each of the two task orders. RTs of Task 2 should increase at short SOAs, where central processing stages of the two tasks come into conflict compared to long SOAs, where no conflict should be apparent (see Figure 5.1a). Second, with a functional bottleneck being active the RTs for Task 2 at short SOAs should strongly depend on RTs for Task 1. This dependency should decrease with SOA. At short SOA variations in the duration of central processing of Task 1 directly influence the bottleneck delay for Task 2. Increasing the SOA Task 1 is no longer delays Task 2. Task 2 no longer depends on Task 1 processing.

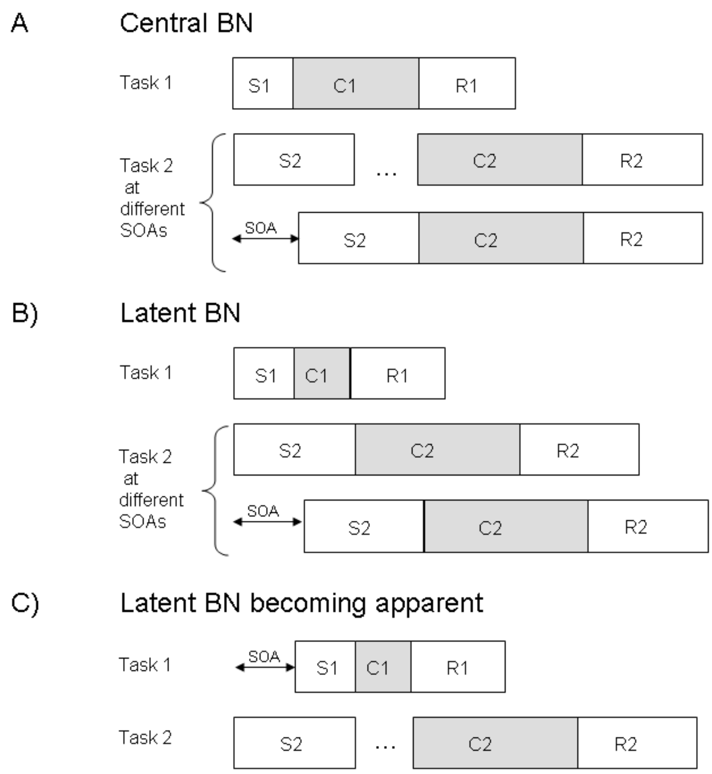

Figure.5.1 Stage-time diagrams where processing is decomposed into three stages labeled with S for stimulus encoding, C for central processing and R for response execution. The numbers denote the membership to Task 1 and 2, respectively. (a) The central response selection bottleneck model. Stages S and R can proceed in parallel with any stage of the other task. However, Stage C (the bottleneck stage) proceeds on only one task at a time for the zero and the short SOA. At long SOA stage C1 generally finishes before Stage C2 is set to begin. (b) Latent bottleneck situation. Stage C can proceed on only one task at a time. However, Stage C1 generally finishes before Stage C2 is set to begin even at an SOA of zero. Hence, at any positive SOA Stage C1 finishes before Stage C2 is set to begin. This situation refers to a latent bottleneck. (c) Latent bottleneck becomes apparent again with the use of sufficiently negative SOA with Task 1 that is actually presented second but encouraged to be processed first.

Next to the C-R Non Standard groups, also the C-R Standard groups were transferred to the PRP paradigm. The practice data of Experiment 3 yielded non significant dual-task costs for the C-R Standard groups at the end of practice. This was attributed to parallel processing for the two groups. Two lines of argument, however, could more or less challenge the interpretation. The first is the single-task baseline that was used for the calculation of dual-task costs in the SPP. Single-task RTs from mix blocks were used as a single-task baseline. In mix blocks single-task trials of one task (manual or vocal) were intermixed with single-task trials of another task and dual-task trials. In contrast to mix blocks in single-task blocks pure single-task trials of only one task were performed throughout the whole block. Single-task RTs of mix blocks were longer than single-task RTs of single-task blocks. This was true even at the end of practice and even though only nonswitch trials were considered for the single-task RTs of mix blocks. Hence, using single-task RTs of mix blocks as a baseline for the calculation of dual-task costs could have deflated the amount of dual-task costs. Mixing single-task RTs have been criticized therefore to be an inappropriate measurement to calculate dual-task costs (Tombu & Jolicoeur, 2004). Dual-task costs of the C-R Standard groups in the SPP could have been masked due this inadequate baseline.

For the PRP paradigm that is used in the present experiment the single-task baseline is not challenged. In the PRP paradigm the single-task baseline for the calculation of dual-task costs (i.e. the PRP effect) is the RT of Task 2 at the longest SOA. Typically, at the longest SOA Task 1 response is already given and participants can therefore focus entirely on Task 2 processing. Proponents of the bottleneck account postulate that RT2 at the long SOA does not suffer interference and represents an appropriate measure of the baseline RT of Task 2 (e.g. Lien, Ruthruff, & Johnston, 2006). Assuming the dual-task baseline of the SPP to be inadequate, dual-task costs should reemerge for the C-R Standard groups. The RTs for Tasks 2 and the correlations between Task 1 and Task 2 should decrease with increasing SOA in the present PRP paradigm. In contrast, if parallel processing was reached, no PRP effect on Task 2 should be observable and RT1- RT2 correlations should not show a dependency on SOA.

The second challenge for the parallel processing interpretation of the C-R Standard groups is the latent bottleneck interpretation (see Figure 5.1b). It has already been discussed to be less likely for the data of the C-R Standard groups. Nevertheless, the present PRP experiment can easily test its explanatory range directly. A latent bottleneck happens when the stimulus encoding stage of one task together with its bottleneck stage take at least as long as the stimulus encoding stage of the other task. This situation leads to a bypass of the bottleneck, i.e. no dual-task costs can be observed although central processing is still serial. The Discussion section of Experiment 3 reviewed two different scenarios of a latent bottleneck: the “spatial task first” and the “auditory task first” scenarios (for a detailed description see the Discussion section of Experiment 3). Especially the “auditory task first” scenario has been discussed to be rather unlikely since it also made the (wrong) prediction of a latent bottleneck for Group 3 (S-R Standard, C-R Non Standard). However, Group 3 exhibited strong dual-task costs. The “spatial task first” scenario also holds some aspects that make it rather unlikely as an explanation for the vanished dual-task costs of the C-R Standard groups. Nevertheless, it is based on a certain characteristic of the C-R Standard groups, i.e. short single-task RTs of the manual tasks that were observable for the C-R Standard but not for the C-R Non Standard groups. Moreover, it only predicts a latent bottleneck for the C-R Standard groups. Therefore, I have decided to test this latent bottleneck scenario for the C-R Standard groups. It postulates that the vanished dual-task costs observed in the C-R Standard groups are due to the stimulus encoding plus central processing stages of the manual task being at least as long as the stimulus encoding stage of the vocal task. Hence it predicts that the spatial-manual task is always processed first for the C-R Standard groups. Using only a zero or positive SOA cannot directly rule out this scenario. No positive SOA would produce a conflict of the processing of central stages (see Figure 5.1b). Here, a short negative SOA is needed to make the latent bottleneck visible again. A negative SOA implies that Task 2, i.e. the vocal task in the present case is shortly presented before Task 1, i.e. the manual task. Assuming a processing bottleneck, expectations rather than actual presentation order were found to determine the processing order of the two stimuli (De Jong, 1995; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). Hence, although the vocal task will be presented first for the negative SOA the manual task is assumed to enter the bottleneck first. As can be seen in Figure 5.1c, the introduction of a negative SOA, would again lead to the conflict of the central processing stages of the two tasks if a bottleneck is still present. The RTs of the vocal task should be prolonged at the negative SOA compared to any positive SOA. The same applies to the correlations between RTs of Task 1 and Task 2. Correlations should be increased for the negative SOA compared to the other positive SOAs. However, when the vocal task has to be processed first, a negative SOA is not needed to make a potential bottleneck visible for the C-R Standard groups. For this processing order the RTs of the manual task should linearly decrease from short positive SOA to the long positive SOA. The prediction for this processing order (vocal task processed first) is the same for the latent bottleneck and the inappropriate baseline assumptions both postulating a bottleneck for the C-R Standard groups.

For the processing order in which the manual task is processed first the two assumptions differ in their predictions. Whereas the latent bottleneck assumption predicts an increase in vocal RT2 exclusively for the negative compared to the positive SOAs, the inappropriate baseline assumption predicts a gradual decrease in vocal RT2s from the shortest, i.e. negative to the longest SOAs.

As such, the transfer of the C-R Standard groups to the PRP paradigm can unequivocally test the latent bottleneck assumption (”spatial task first” scenario) and the postulation of deflated dual-task costs due to a less conservative single baseline in Experiment 3 as an explanation of the observed vanished dual-task costs.

To summarize, the aim of the present experiment is to test whether the result of vanished dual-task costs for the C-R Standard groups can be replicated within the PRP paradigm, thereby confirming the interpretation of parallel processing for these groups. Furthermore, the experiment tests whether residual dual-task costs for the C-R Non Standard groups have to be attributed to mere crosstalk or whether an additional bottleneck was present.

5.1. Method

Participants. The same 24 individuals from Experiment 3 participated in Experiment 4. Participants received five Euro per session or course credit. They could earn extra reward for fast and accurate responding in the form of money or course credit.

Design and Procedure. The four groups and their respective tasks remained the same as in Experiment 3. Experiment 4 consisted of two sessions, which followed the eight sessions of Experiment 3. The maximal time gap between the experiments was one week. The design of the two sessions was equal across groups. Each session consisted of 16 blocks. Each block consisted of twelve trials for each single task (vocal or manual) and of 36 dual-task trials, that were intermixed randomly.

The material and the procedure of a single-task trial were the same as in Experiment 3. The dual-task trials differed from Experiment 3 only with respect to the SOA that separated the tasks. Participants were informed that in the dual-task trials of Experiment 4 the two tasks were no longer presented simultaneously but separated by an SOA. They were informed that the task that was (mostly) presented first during one session had to be prioritized. The priority was varied across sessions. Hence, in one session participants were instructed to emphasize the vocal task and in the other session the manual task. Participants were informed repeatedly about priority of the actual session, which was displayed on the screen prior to each block. The order of priority was counterbalanced across participants.

For each session there were four different SOAs. The SOAs partly differed depending on priority and group. The SOAs for Group 1 and 2 in the vocal priority condition were: 50, 150, 200 and 800 ms, in the manual priority condition: -50, 50, 200 and 800 ms. The negative SOA in the manual priority condition means that the vocal task was actually presented first for this single SOA. Nevertheless the manual task had to be prioritized in this session. This negative SOA was implemented to make a possible latent bottleneck visible again for the manual priority condition. For Group 3 and 4 the SOAs for both task orders were 50, 150, 250 and 1000 ms. The longest SOA differed between the groups (1000 ms vs. 800 ms) to take the longer manual single-task RTs for the C-R Non Standard compared to the Standard pairing groups into account. The long SOA shall guarantee that the central phases of the two tasks do not overlap in time. The SOA for each trial was randomly selected from the set of the appropriate four SOAs with the restriction that every SOA occurred 144 times in one session.

The percent correct rate for the manual task as well as the mean RTs of the manual and the vocal task were displayed at the end of a block. The RT deadline of the next block was displayed prior to each block and was based on the mean RT of the preceding block. The initial deadline was fixed to 2000 ms. Participants were instructed to respond quickly and accurately. They earned reward for meeting the RT deadline in each task and for each percent correct point above 90% of each task. They lost reward for exceeding the deadline and for each percent correct point under 90%. The reward algorithm was the same as in Experiment 3.

5.2. Results

Excluded from further analyses were erroneous trials of either task, RTs that were faster than 200 ms or slower than three *SD*s from the individual mean of that session and processing condition. 3.4% of the data were excluded. The results for the single-task trials that were presented intermixed with the dual-task trials were moved to the Appendix C. The results mirror the results of Experiment 3. In the following each group is regarded separately. For each group separate ANOVAs were conducted testing the effect of SOA and output modality (manual vs. vocal) on the RT and PE data for Task 1 and Task 2. Furthermore, for each priority condition it was examined whether the RT1: RT2 correlations decreased with increasing SOA.

Group 1 (S-R Standard, C-R Standard). Table 5.1 summarizes the results for Task 1 of Group 1. The RTs of the manual Task 1 were shorter than the RTs of the vocal Task 1. There was no significant effect of SOA observable on manual and vocal Task 1s. The Figures 5.2a and 5.2b display the mean RTs of the manual and the vocal Task 1, respectively as a function of SOA.

For the PEs of the manual and vocal Task 1 there was, over all, no effect of SOA observable (see Table 5.1). The manual Task 1 errors showed a quadratic distribution over SOA with an increase for the shortest and the longest SOA. This trend missed the conventional level of significance in a separate analysis (Table 5.2) on manual Task 1 errors. No such trend observable for the vocal Task 1 PEs.

Table 5.1. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 1 for Group 1 (S-R Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 1 (manual and vocal)	Output modality	90.05 (1, 5)	.947	<.001
		SOA (linear)	4.66 (1, 5)	.482	.083
		SOA (quadratic)	3.58 (1, 5)	.417	.117
		Output modality * SOA (linear)	1.23 (1, 5)	.197	.318
		Output modality *SOA (quadratic)	.21 (1, 5)	.039	.670
PE	Task 1 (manual and vocal)	Output modality	.04 (1, 5)	.008	.852
		SOA (linear)	.02 (1, 5)	.005	.882
		SOA (quadratic)	3.86 (1, 5)	.436	.107
		Output modality * SOA (linear)	.20 (1, 5)	.038	.674
		Output modality *SOA (quadratic)	6.17 (1, 5)	.552	.056

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.2. Summary of the ANOVA results testing the effect of SOA on PEs of the manual and vocal Task 1 for Group 1 (S-R Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
PE	Manual Task 1	SOA (linear)	.13 (1, 5)	.025	.732
		SOA (quadratic)	5.92 (1, 5)	.542	.059
	Vocal Task 1	SOA (linear)	.12 (1, 5)	.023	.748
		SOA (quadratic)	1.07 (1, 5)	.176	.348

Figures 5.2a and 5.2b display the mean RTs for the vocal and the manual task 2, respectively as a function of SOA. The predictions of the latent bottleneck and the inappropriate baseline assumption concerning the PRP effect on the manual and the vcoal task 2 were tested. The inappropriate baseline assumption postulates a significant increase of RTs from the longest to the shortest SOA for both the manual and the vocal task 2. Since neither the linear contrast for the SOA factor, nor its interaction with output modality (manual or vocal) did reach significance, there was no PRP effect observable on either task 2 of Group 1 (see Table 5.3) that would support the inappropriate baseline assumption.

The latent bottleneck makes the same prediction as the inappropriate baseline assumption with respect to the manual task 2. However, this prediction can be ruled out due the nonsignificant SOA and SOA x output modality effects of the overall ANOVA (Table 5.1). However, for the vocal task 2 the latent bottleneck assumption predicts an increase at the -50 ms SOA compared to the other SOAs. Consequently, this contrast was conducted separately on the RTs of vocal task 2 of Group 1. Table 5.4 shows the results for this contrast. There was no increase of the vocal task 2 at the -50 ms SOA compared to the longer SOAs.

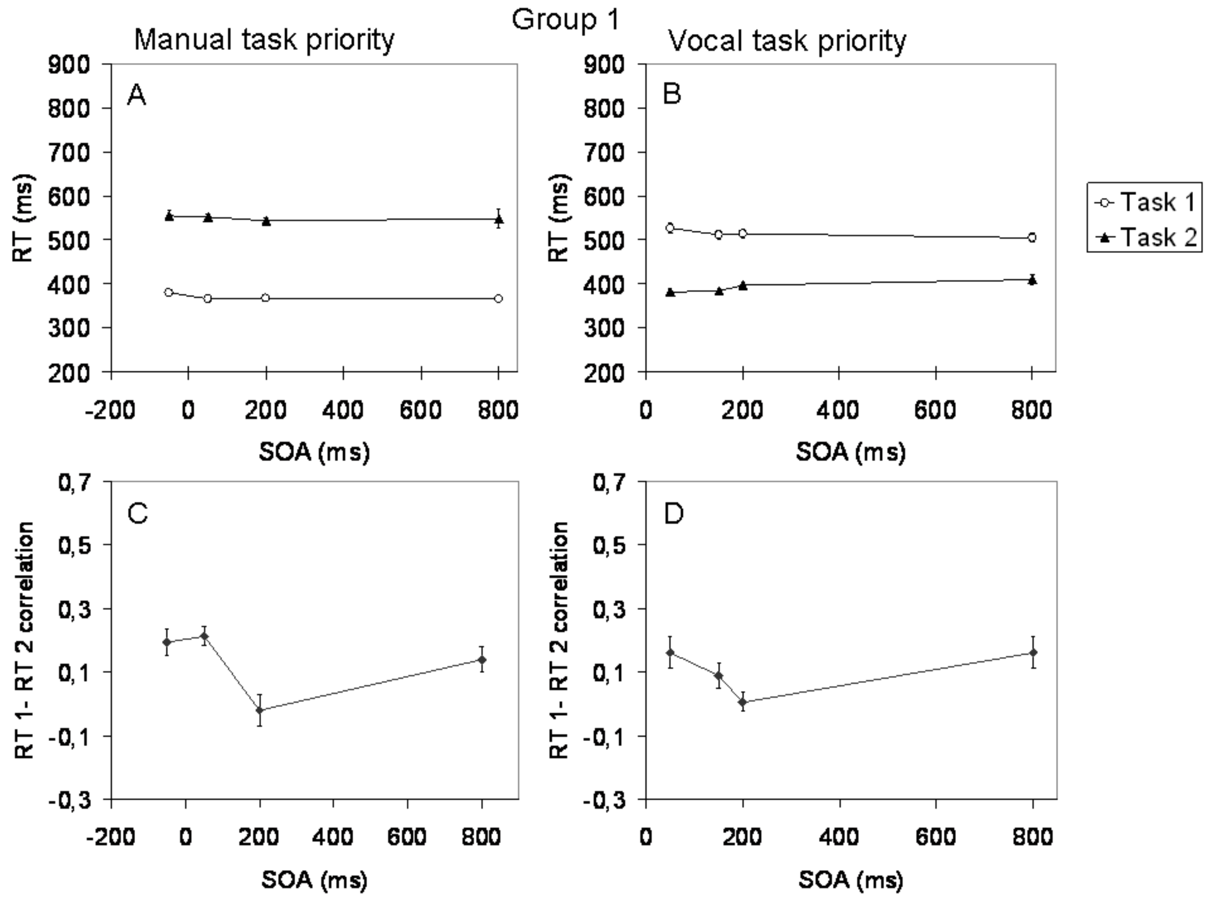

Fig. 5.2. Mean RTs to Task 1 and Task 2 as a function of the SOA for the manual priority (a) and the vocal priority-condition (b) of Group 1. In the bottom part of the figure the correlation coefficients of the manual priority (c) and the vocal priority-condition (d) are displayed as a function of SOA. Error bars represent standard errors for repeated measures computed by the method of Bakeman and McArthur (1996).

Table 5.3 summarizes the analysis of the error data for the manual and the vocal task 2 of Group 1. There were more errors done on the manual than on the vocal task 2. There was no effect of SOA on the errors of the manual and vocal task 2. The error data therefore confirm the picture that no PRP effect was observed for both the manual and the vocal tasks 2 of Group 1.

Table 5.3. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 2 for Group 1 (S-R Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 2	Output modality	39.40 (1, 5)	.887	.002
	(manual	SOA (linear)	.78 (1, 5)	.135	.417
	and	SOA (quadratic)	.37 (1, 5)	.068	.572
	vocal)	Output modality * SOA (linear)	2.63 (1, 5)	.345	.166
		Output modality *SOA (quadratic)	<.01 (1, 5)	.001	.958
PE	Task 2	Output modality	39.40 (1, 5)	.887	.002
	(manual	SOA (linear)	.06 (1, 5)	.011	.822
	and	SOA (quadratic)	4.25 (1, 5)	.459	.094
	vocal)	Output modality * SOA (linear)	.83 (1, 5)	.142	.405
		Output modality *SOA (quadratic)	1.35 (1, 5)	.213	.298

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.4. Summary of the ANOVA results testing the effect of SOA on the RTs and PEs of the vocal task 2 for the latent bottleneck assumption of Group 1 (S-R Standard, C-R Standard).

DV	Effect	*F*(df)	partial η^2	*p*
RT	SOA (1st to other)	1.34 (1, 5)	.212	.299
PE	SOA (1st to other)	.094 (1, 5)	.019	.771

Furthermore, it was examined whether the dependency between the speed of the second response and the speed of the corresponding first response increased for short compared to long SOA. Separately for each SOA, priority and participant the standardized slopes describing RT2 as a function of RT1 were computed. For this bivariate case the standardized regression coefficients can be interpreted as correlation coefficients. The correlation coefficients were Fisher’s Z transformed to comply with the ANOVA precondition of normal distribution. The correlations were subjected to a repeated-measure ANOVA with SOA as the within-subject factor. Mean correlations presented in figures or tables, however, were untransformed correlation coefficients. For Group 1 the Figures 5.2c and d display the correlations between the RTs of Task 1 and Task 2 for the manual and the vocal priority, respectively as a function of SOA.

The inappropriate baseline assumption postulates correlations between RT1 and RT2 to decrease with increasing SOA in both priority conditions. Table 5.5 summarises the test statistics of the analysis. For the manual priority condition there was a decrease in RT1: RT2 correlations from the second to the third SOA with an increase for the last SOA. Correlations in the vocal priority condition also decreased and increased again for the last SOA. Non of the effects reached the conventional level of significance.

The latent bottleneck assumption assumes highest correlations to be present for the -50 ms SOA in the manual- priority condition. The results of the analysis (see Table 5.5) show that no increase for the shortest SOA was observable. Moreover, correlations were very low and partly did not differ from zero (see Table 5.6).

Table 5.5. Summary of the ANOVA results testing the effect of SOA on the RT1-RT2 Fisher's Z transformed correlation coefficients for the vocal priority condition of Group 1 (S-R Standard, C-R Standard).

Task priority	Effect	*F*(df)	partial η^2	*p*
Vocal	SOA (linear)	(1, 5) .11	.021	.756
	SOA (quadratic)	(1, 5) 7.51	.600	.041
Manual	SOA (linear)	4.89 (1, 5)	.494	.078
	SOA (quadratic)	1.42 (1, 5)	.221	.278
	SOA (1st to other)	2.46 (1, 5)	.330	.178

Table 5.6. Overview of the correlations between Task 1 and task 2 RTs at different SOAs and for the different priority conditions of Group 1.

Group	Manual priority				Vocal priority			
	SOA	*M* (*SD*)	*T* (df)	*p*	SOA	*M* (*SD*)	*T*(df)	*p*
1 (S-R	-50	.19 (.11)	4.19 (5)	.009	50	.16 (.13)	3.13 (5)	.026
Standard, C-R	50	.21 (.07)	.7.43 (5)	.001	150	.09 (.15)	1.50 (5)	.194
Standard)	200	-.02 (.10)	-.48 (5)	.652	200	.01 (.08)	.20 (5)	.851
	800	.14 (.12)	2.80 (5)	.038	800	.16 (.12)	3.36 (5)	.020

Note. Mean correlations with Standard Deviations (in brackets) as a function of SOA and priority; *T*-values for the test against zero are given with degrees of freedom and *p*-values.

Taken together there is no evidence for a PRP effect on RT2 for any task-priority condition of Group 1. Table 5.25 summarizes the effects of SOA on the RTs, PEs and the correlations of Task 1 and Task 2. The result rule out the latent bottleneck and the inappropriate baseline assumption for Group 1. It supports the view of parallel processing of the two tasks for Group 1.

Group 2 (S-R Non Standard, C-R Standard). Figures 5.3a and b display the RTs of the manual and of the vocal Task 1 of Group 2 as a function of SOA.

An ANOVA with SOA as within-subject factor was conducted on the RTs of both, the manual and the vocal Task 1 of the Group 2. Table 5.7 displays the results. The manual tasks were faster than the vocal tasks. There was an overall quadratic trend of SOA on the Task 1 RTs of Group 2. This effect shows that for the middle SOAs the RTs increased in comparison to the shortest and the longest SOAs. The SOA effect was different for the manual and the vocal Task 1. Separate ANOVAs (Table 5.8) exhibited that the manual task showed a decrease in RT for short SOAs and the vocal task showed a significant quadratic contrast of the SOA effect with longer RTs for the middle SOAs.

The results of the ANOVA on the Task 1 PEs of Group 2 are summarized in Table 5.7. They show that the manual Task 1 exhibited more errors than the vocal Task 1. The errors increased for the shortest SOA. The manual and the vocal task exhibited different trends over the SOAs. The separate ANOVAs summarized in Table 5.8, show that for the manual task the errors increased for the shortest SOA but stayed constant for the other SOAs. The vocal task errors did not vary with SOA.

Table 5.7. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 1 for Group 2 (S-R Non Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 1	Output modality	76.96 (1, 5)	.939	<.001
	(manual	SOA (linear)	1.03 (1, 5)	.171	.356
	and	SOA (quadratic)	19.85 (1, 5)	.799	.007
	vocal)	Output modality * SOA (linear)	5.67 (1, 5)	.531	.063
		Output modality *SOA (quadratic)	4.72 (1, 5)	.485	.082
PE	Task 1	Output modality	.04 (1, 5)	.008	.852
	(manual	SOA (linear)	.02 (1, 5)	.005	.882
	and	SOA (quadratic)	3.86 (1, 5)	.436	.107
	vocal)	Output modality * SOA (linear)	.20 (1, 5)	.038	.674
		Output modality *SOA (quadratic)	(6.17 (1, 5)	.552	.056

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.8. Summary of the ANOVA results testing the effect of SOA on RTs and PEs of the manual and vocal Task 1 for Group 2 (S-R Non Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Manual	SOA (linear)	6.60 (1, 5)	.569	.050
	Task 1	SOA (quadratic)	6.13 (1, 5)	.551	.056
	Vocal	SOA (linear)	2.67 (1, 5)	.348	.163
	Task 1	SOA (quadratic)	10.78 (1, 5)	.683	.022
PE	Manual	SOA (linear)	18.02 (1, 5)	.783	.008
	Task 1	SOA (quadratic)	7.89 (1, 5)	.612	.038
	Vocal	SOA (linear)	.25 (1, 5)	.048	.637
	Task 1	SOA (quadratic)	1.05 (1, 5)	.174	.352

Figures 5.3a and b show the RTs of the manual and the vocal task 2 as a function of SOA. The predictions of the inappropriate baseline and the latent bottleneck assumption with respect to the Task 2 PRP effects were tested. The results testing the inappropriate baseline assumption are summarized in Table 5.9 (linear decrease with increasing SOA). A quadratic trend of the overall SOA effect became significant, indicating the longest RT on the third SOA and about equal RTs for the other SOAs. The SOA factor affected the two tasks differently. Hence, separate ANOVAs for the manual and the vocal task were conducted. Table 5.10 summarizes them. For the manual task 2 the RTs increased with increasing SOA. This is an inverse PRP effect and opposite to what had been predicted on the basis of the inappropriate baseline assumption. The vocal task 2 showed a significant quadratic trend of

the SOA factor on the RTs with about equal RTs at the first three SOAs and a decrease in RT for the longest SOA. This effect comprises about 65 ms from the shortest to the longest SOA. There was, however, no linear trend observable.

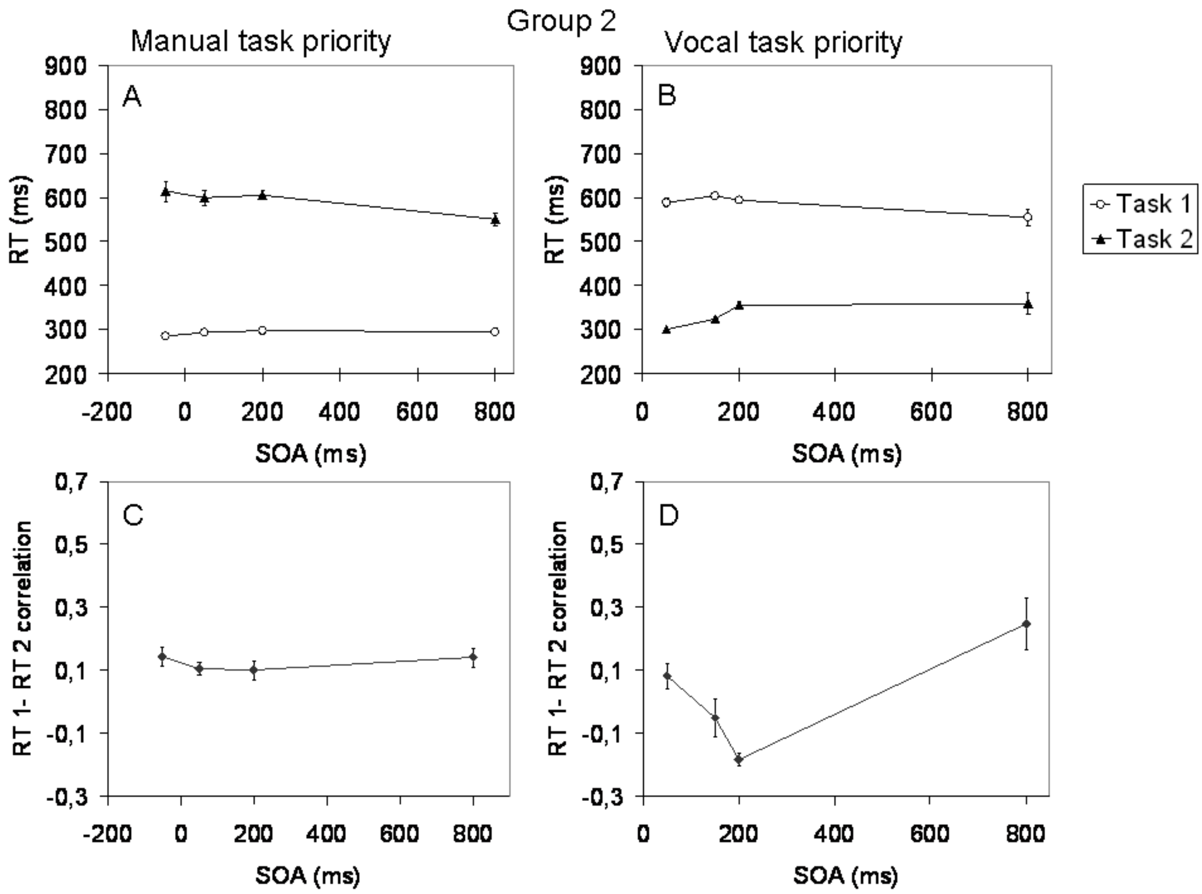

Fig. 5.3. Mean RTs of Task 1 and Task 2 as a function of the SOA for the manual priority (a) and the vocal priority condition (a) of Group 2. In the bottom part of the figure the correlation coefficients of the manual priority (c) and the vocal priority-condition (d) are displayed as a function of SOA. Error bars represent standard errors for repeated measures computed by the method of Bakeman and McArthur (1996).

The latent bottleneck assumption makes the same prediction as the inappropriate baseline assumption with respect to the linear decrease of the RTs for the manual task 2. As already reported the inverse effect was observable. For the vocal task 2 the latent bottleneck assumption predicts an increase in RTs that should be apparent exclusively at -50 ms SOA. This is because any SOA equal and greater than zero should make the bottleneck latent again. However, contrasting the RTs of the first SOA to the mean of the other SOAs, it becomes obvious, that the difference was not significant (see Table 5.11).

The overall ANOVA (see Table 5.9) testing the effect of SOA on the manual and vocal task 2 PEs revealed an increase of the errors with increasing SOA, which describes an opposite PRP effect. The effect of the SOA factor differed for the two tasks. The separate analyses on the manual and vocal task 2 errors are summarized in Table 5.10. For the manual task 2 errors it revealed a reverse PRP effect. Such a reverse PRP effect was also seen for the RTs of the manual task 2. These reverse PRP effects can explain the RT increase for the vocal Task 1 at short SOA as a trade off between the two tasks. There was no effect of SOA on the vocal task 2 errors. The inverse and the absent SOA effect on the PEs of the manual and the vocal task were neither predicted by the inappropriate baseline nor the latent bottleneck assumption (see Tables 5.10 and 5.11).

Table 5.9. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 1 and Task 2 for Group 2 (S-R Non Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 2	Output modality	48.86 (1, 5)	.907	.001
	(manual	SOA (linear)	.06 (1, 5)	.013	.811
	and	SOA (quadratic)	6.79 (1, 5)	.576	.048
	vocal)	Output modality * SOA (linear)	6.61 (1, 5)	.569	.050
		Output modality *SOA (quadratic)	.79 (1, 5)	.137	.414
PE	Task 2	Output modality	21.36 (1, 5)	.810	.006
	(manual	SOA (linear)	12.36 (1, 5)	.712	.017
	and	SOA (quadratic)	1.45 (1, 5)	.225	.282
	vocal)	Output modality * SOA (linear)	14.63 (1, 5)	.745	.012
		Output modality *SOA (quadratic)	2.14 (1, 5)	.300	.203

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.10. Summary of the ANOVA results testing the effect of SOA on RTs and PEs of the manual and vocal task 2 for Group 2 (S-R Non Standard, C-R Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Manual	SOA (linear)	6.80 (1, 5)	.580	.047
	task 2	SOA (quadratic)	1.10 (1, 5)	.180	.342
	Vocal	SOA (linear)	3.90 (1, 5)	.439	.105
	task 2	SOA (quadratic)	9.72 (1, 5)	.660	.026
PE	Manual	SOA (linear)	13.61 (1, 5)	.731	.014
	task 2	SOA (quadratic)	2.00 (1, 5)	.286	.216
	Vocal	SOA (linear)	.640 (1, 5)	.113	.460
	task 2	SOA (quadratic)	.488 (1, 5)	.689	.516

Table 5.11. Summary of the ANOVA results testing the effect of SOA on the RTs and PEs of the vocal task 2 for the latent bottleneck assumption of Group 2 (S-R Non Standard, C-R Standard).

DV	Effect	*F*(df)	partial η^2	*p*
RT	SOA (1st to other)	3.11 (1, 5)	.383	.138
PE	SOA (1st to other)	.11 (1, 5)	.022	.750

The correlations between RT1 and RT2 of Group 2 are displayed in Figures 5.3c and d as a function of SOA for the manual and the vocal priority condition, respectively. The analyses on the correlation coefficients (see Table 5.12) revealed no effect of SOA except a significant quadratic trend of SOA for the vocal priority condition. This effect was due to the correlations reducing with SOA thereby reaching significant negative values for the 200 ms SOA but increasing for the longest SOA (see Table 5.13).

Table 5.12. Summary of the ANOVA results testing the effect of SOA on the RT1-RT2 Fisher's Z transformed correlation coefficients for the vocal priority condition of Group 2 (S-R Non Standard, C-R Standard).

Task priority	Effect	*F*(df)	partial η^2	*p*
Vocal	SOA (linear)	(1, 5) 1.07	.176	.349
	SOA (quadratic)	(1, 5) 26.20	.840	.004
Manual	SOA (linear)	>.01 (1, 5)	.001	.951
	SOA (quadratic)	1.28 (1, 5)	.203	.310
	SOA (1st to other)	.39 (1, 5)	.072	.560

Table 5.13. Overview of the correlations between RTs for Task 1 and Task 2 at different SOAs and for the different task-priority conditions of Group 2.

Group	Manual priority				Vocal priority			
	SOA	*M* (*SD*)	*T* (df)	*p*	SOA	*M* (*SD*)	*T*(df)	*p*
2 (S-R Non	-50	.14 (.08)	(5) 4.56	.006	50	.08 (.12)	(5) 1.71	.147
Standard,	50	.10 (.10)	(5) 2.47	.056	150	-.05 (.17)	(5) -.73	.498
C-R Standard)	200	.10 (.10)	(5) 2.62	.047	200	-.18 (.06)	(5) -7.56	.001
	800	.14 (.10)	(5) 3.84	.012	800	.25 (.20)	(5) 3.00	.030

Note. Mean correlations with Standard Deviations (in brackets) as a function of SOA and priority; *T*-values for the test against zero are given with degrees of freedom and *p*-values.

Table 5.25 summarizes the SOA effects for Group 2 on the RTs, PEs and RT1- RT2 correlations of each priority condition. For Group 2 in the manual priority condition there was a PRP effect on vocal task 2 observable, which had a magnitude of 65 ms (longest-shortest SOA). This effect was only due to the decrease of vocal RTs on the longest SOA. The bottleneck account would, however, predict a linear decrease. Moreover, at the same time with the increase of vocal RT2 at short SOA there was an opposite effect on the manual Task 1 observable. A similar picture was apparent for the vocal priority condition, where an opposite PRP effect for the manual task 2 was observable with an increase in RTs at short SOAs for the vocal Task 1. For this priority condition even negative RT1: RT2 correlations were found.

Group 3 (S-R Standard, C-R Non Standard). The RTs of the manual and the vocal Task 1 of Group 3 are displayed as a function of SOA in Figures 5.4a and b. Analysing the effect of SOA as within and output modality as between-subject factor on the RTs of the Task 1 for Group 3 the effect of SOA was significant. RTs for the manual and the vocal Task 1 increased with decreasing SOA (see Table 5.14).

The manual task exhibited less errors than the vocal Task 1 (Table 5.14.). The errors of the vocal Task 1 showed an increase for shorter SOAs, which was absent for the manual task. Separate ANOVAs on the errors of the manual and the vocal Task 1, however, revealed no significant effect of SOA on either task (see Table 5.15).

Table 5.14. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 1 for Group 3 (S-R Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 1	Output modality	1.58 (1, 5)	.240	.265
	(manual	SOA (linear)	12.24 (1, 5)	.710	.017
	and	SOA (quadratic)	16.43 (1, 5)	.767	.010
	vocal)	Output modality * SOA (linear)	1.77 (1, 5)	.262	.241
		Output modality *SOA (quadratic)	.06 (1, 5)	.011	.821
PE	Task 1	Output modality	8.90 (1, 5)	.640	.031
	(manual	SOA (linear)	2.98 (1, 5)	.374	.145
	and	SOA (quadratic)	1.35 (1, 5)	.213	.297
	vocal)	Output modality * SOA (linear)	11.51 (1, 5)	.697	.019
		Output modality *SOA (quadratic)	.03 (1, 5)	.006	.872

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.15. Summary of the ANOVA results testing the effect of SOA on PEs of the manual and vocal Task 1 for Group 3 (S-R Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
PE	Manual	SOA (linear)	.41 (1, 5)	.076	.549
	Task 1	SOA (quadratic)	.03 (1, 5)	.006	.867
	Vocal	SOA (linear)	1.42 (1, 5)	.221	.287
	Task 1	SOA (quadratic)	3.96 (1, 5)	.442	.103

The analysis on the manual and vocal task 2 of Group 3 showed that the RTs for the manual task were shorter than for the vocal task (Table 5.16). A significant PRP effect was observed that was equal for the two tasks. The PRP effects for the vocal and the manual task 2 are displayed in Figure 5.4a and b, respectively.

Errors were less frequent for the manual compared to the vocal task 2 (Table 5.16). The vocal task 2 errors increased with decreasing SOA while the manual task errors rather showed a decrease for short SOAs. Separate ANOVAs on the manual and the vocal task 2 errors revealed a significant effect of SOA on the vocal task errors (Table 5.17). In contrast the effect for the manual Task 1 errors missed the conventional level of significance.

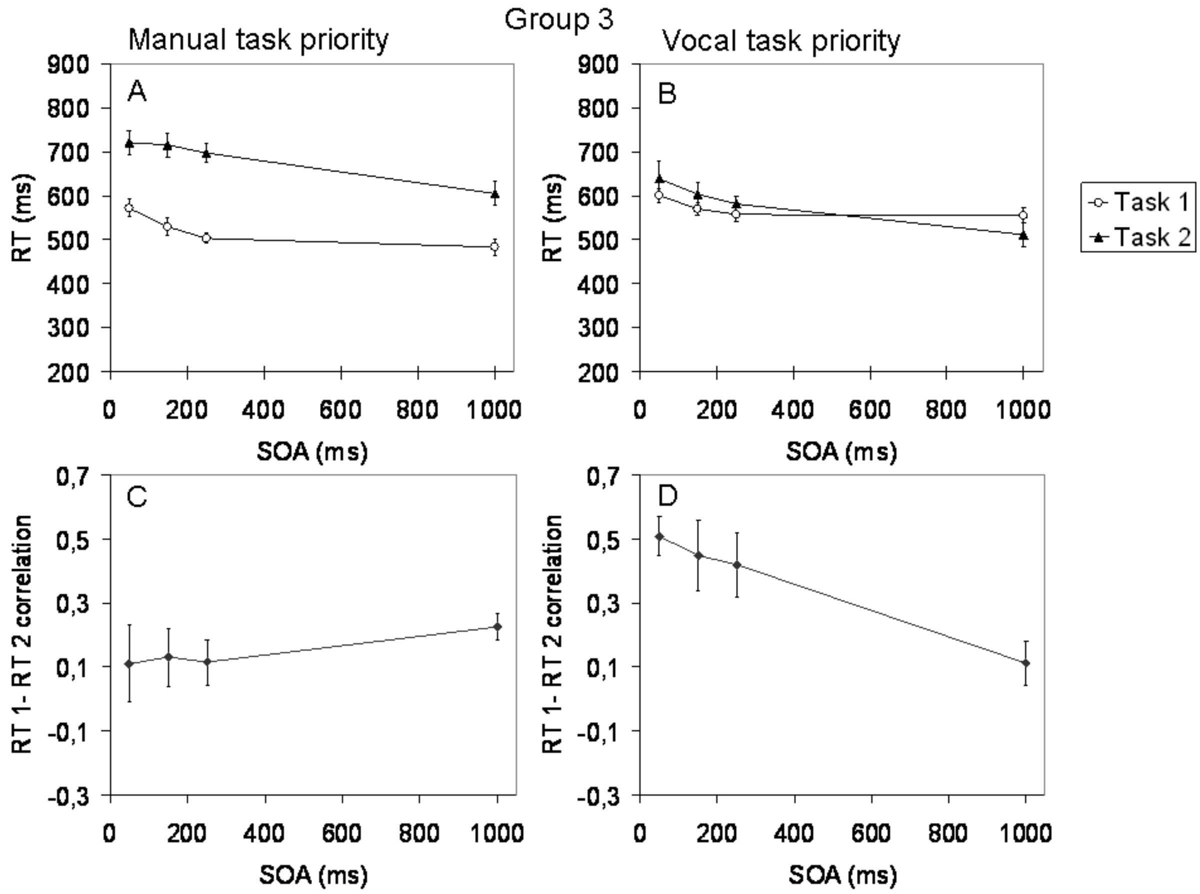

Figure 5.4. Mean RTs to Task 1 and Task 2 as a function of the SOA for the manual priority (a) and the vocal priority condition (b) of Group 3. In the bottom part of the figure the correlation coefficients of the manual priority (c) and the vocal priority condition (d) are displayed as a function of SOA. Error bars represent standard errors for repeated measures computed by the method of Bakeman and McArthur (1996).

Table 5.16. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 2 for Group 3 (S-R Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 2	task	9.93 (1, 5)	.665	.025
	(manual	SOA (linear)	6.69 (1, 5)	.572	.049
	and	SOA (quadratic)	8.01 (1, 5)	.616	.037
	vocal)	Output modality * SOA (linear)	.06 (1, 5)	.012	.817
		Output modality *SOA (quadratic)	5.01 (1, 5)	.500	.075
PE	Task 2	Output modality	15.58 (1, 5)	.757	.011
	(manual	SOA (linear)	1.10 (1, 5)	.180	.343
	and	SOA (quadratic)	1.37 (1, 5)	.215	.204
	vocal)	Output modality * SOA (linear)	1.61 (1, 5)	.244	.260
		Output modality *SOA (quadratic)	13.50 (1, 5)	.730	.014

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.17. Summary of the ANOVA results testing the effect of SOA on PEs of the manual and vocal task 2 for Group 3 (S-R Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
PE	Manual	SOA (linear)	4.48 (1, 5)	.472	.088
	task 2	SOA (quadratic)	.75 (1, 5)	.130	.428
	Vocal	SOA (linear)	14.48 (1, 5)	.743	.013
	task 2	SOA (quadratic)	.48 (1, 5)	.088	.519

The correlation coefficients are displayed as a function of SOA for the manual and the vocal priority condition in Figure 5.4c and d, respectively. Only for the vocal priority condition correlations decreased with increasing SOA, not for the manual priority condition (Table 5.18).

Table 5.18. Summary of the ANOVA results testing the effect of SOA on the RT1-RT2 Fisher's Z transformed correlation coefficients for the vocal priority condition of Group 3 (S-R Standard, C-R Non Standard).

Task priority	Effect	*F*(df)	partial η^2	*p*
Vocal	SOA (linear)	(1, 5) 9.89	.664	.026
	SOA (quadratic)	(1, 5) 1.41	.220	.288
Manual	SOA (linear)	.55 (1, 5)	.099	.492
	SOA (quadratic)	.25 (1, 5)	.047	.639

Table 5.19. Overview of the correlations between the RTs for Task 1 and Task 2 at different SOAs for the different priority conditions of Group 3.

Group	Manual priority				Vocal priority			
	SOA	*M* (*SD*)	*T* (df)	*p*	SOA	*M* (*SD*)	*T*(df)	*p*
3 (S-R	50	.11 (.21)	(5) 1.27	.259	50	.51 (.25)	(5) 5.03	.004
Standard,	150	.13 (.12)	(5) 2.73	.047	150	.45 (.41)	(5) 2.70	.043
C-R Non	250	.11 (21)	(5) 1.34	.239	250	.42 (.40)	(5) 2.60	.048
Standard)	1000	.22 (.17)	(5) 3.17	.025	1000	.11 (.18)	(5) 1.52	.189

Note. Mean correlations with Standard Deviations (in brackets) as a function of SOA and priority; *T*-values for the test against zero are given with degrees of freedom and *p*-values.

SOA effects on Task 1 are typically not predicted when a bottleneck alone limits dual-task performance. It is, however, in line with the prediction of the bottleneck with crosstalk account. Nevertheless it can also be explained by assuming a bottleneck with response grouping at short SOAs. Grouping means that at short SOAs participants withhold reaction to Task 1 until R2 had been selected. This is done in order to execute Task 1 with Task 2 in a grouped fashion. Inspection of the distributions of the inter-response intervals (IRI) is a diagnostic tool for response grouping (Pashler, 1994b; Pashler & Johnston, 1989; Ruthruff, Pashler, & Klaassen, 2001). Assuming it for the participants of Group 3 a high percentage of the IRIs for the 50 ms SOA must be around zero. In order to examine this, the percentage of IRIs for the 50 ms SOA within the interval of -100 ms to +100 ms was determined for each participant and priority condition. The result is shown in Figure 5.5. Participant 1 responded in about 40% of the trials within the interval. The other participants clearly showed a lesser tendency to perform responses conjointly. Averaged across participants only 15% of the responses for the manual priority condition laid in this interval.

For the vocal priority condition the percentage of IRIs within the 200 ms interval numerically increased for most participants compared to the manual priority condition. Responses of Participant 4 were given in about 60% of the responses laid within the interval. Averaged across participants 30% of the responses laid with the interval. Hence, response grouping was rather unlikely for the manual priority condition. It, however, cannot be ruled out as a strategy, at least for two participants (Participant 1 in the manual, Participant 4 in the vocal priority condition).

Results are summarized in Table 5.25 displaying the effects of SOA on RTs, PEs and the RT1: RT2 correlations of Group 3 for each priority condition. There were PRP effects on RT2s in each priority condition. One correlation between RT1 and RT2 showed a dependency of SOA that was predicted by the bottleneck account. Also Task 1 in each priority condition increased with decreasing SOA.

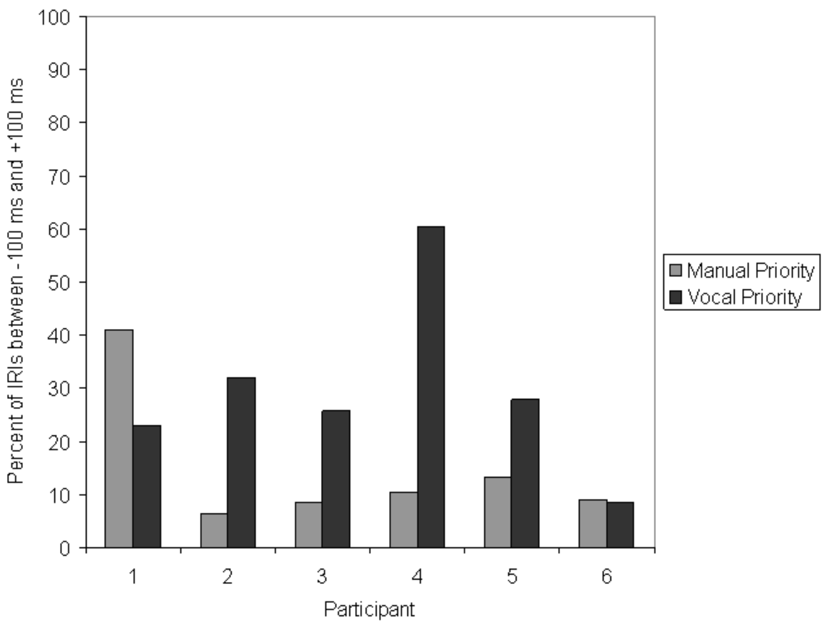

Figure 5.5 Histogram showing the proportion of inter-response intervals (IRIs) lying between -100 ms and +100 ms at the 50 ms SOA for each participant and priority condition of Group 3.

Group 4 (S-R Non Standard, C-R Non Standard). The results of the ANOVA on the RTs for the manual and vocal Task 1 of Group 4 are listed in Table 5.20. The manual Task 1 was faster than the vocal Task 1. For both task, there was a significant effect of SOA observable. Figures 5.5a and b show that the RTs increased with decreasing SOA for the manual and the vocal Task 1, respectively.

A small effect of SOA was also observable on the Task 1 PEs (Table 5.20). This effect was different for the manual and the vocal Task 1 PEs. Separate analyses for each task (Table 5.21.) showed that the manual task exhibited a strong decrease in errors with increasing SOA, which was followed by an increase in errors for the longest SOA. However, the vocal task showed a linear decrease in errors with increasing SOA that missed the conventional level of significance.

Table 5.20. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 1 for Group 4 (S-R Non Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 1	Output modality	6.37 (1, 5)	.560	.053
	(manual	SOA (linear)	23.83 (1, 5)	.827	.005
	and	SOA (quadratic)	3.77 (1, 5)	.430	.110
	vocal)	Output modality * SOA (linear)	.56 (1, 5)	.101	.488
		Output modality *SOA (quadratic)	3.06 (1, 5)	.379	.241
PE	Task 1	Output modality	2.49 (1, 5)	.332	.176
	(manual	SOA (linear)	6.93 (1, 5)	.581	.046
	and	SOA (quadratic)	3.95 (1, 5)	.441	.104
	vocal)	Output modality * SOA (linear)	1.84 (1, 5)	.269	.233
		Output modality *SOA (quadratic)	11.79 (1, 5)	.702	.019

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

Table 5.21. Summary of the ANOVA results testing the effect of SOA on PEs of the manual and vocal Task 1 for Group 4 (S-R non Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
PE	Manual	SOA (linear)	5.67 (1, 5)	.532	.063
	Task 1	SOA (quadratic)	12.62 (1, 5)	.716	.016
	Vocal	SOA (linear)	5.43 (1, 5)	.521	.067
	Task 1	SOA (quadratic)	.01 (1, 5)	.002	.932

Task 2 RTs are displayed in Figure 5.5a and b as a function of SOA for the manual and the vocal priority condition, respectively. The overall analysis revealed that RTs of the manual task 2 were shorter than the RTs of the vocal task 2. A PRP effect was apparent for both Task 2s (Table 5.22). The PEs for the manual task 2 were higher than for the vocal task 2 (Table 5.22). There was no effect of SOA on the PEs for the Task 2s observable.

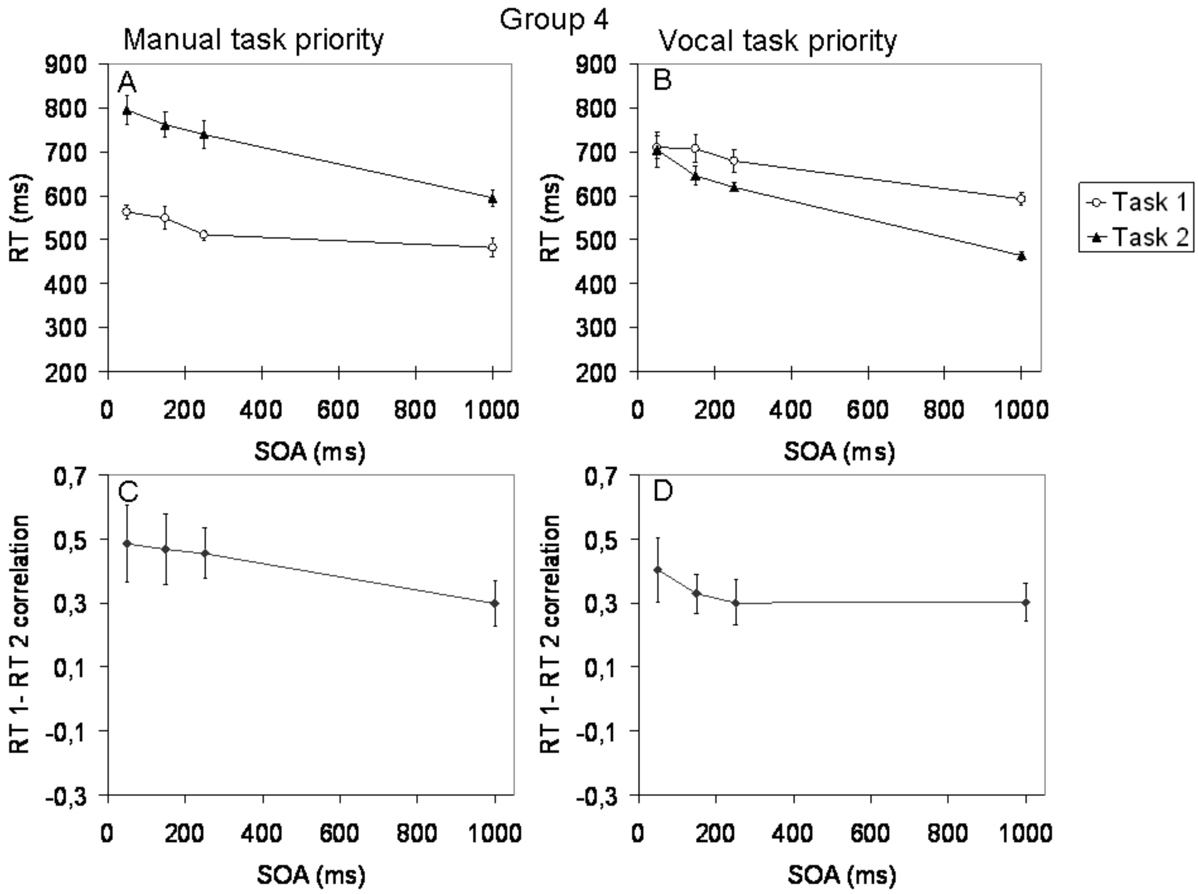

Figure 5.5. Mean RTs to Task 1 and Task 2 as a function of the SOA for the manual priority (a) and the vocal priority condition (b) of Group 4. In the bottom part of the figure the correlation coefficients of the manual priority (c) and the vocal priority condition (d) are displayed as a function of SOA. Error bars represent standard errors for repeated measures computed by the method of Bakeman and McArthur (1996).

Table 5.22. Summary of the ANOVA results testing the effects of SOA and output modality on RTs and PEs of Task 2 for Group 4 (S-R Non Standard, C-R Non Standard).

DV	Task	Effect	*F*(df)	partial η^2	*p*
RT	Task 2	Output modality	30.06 (1, 5)	.857	.003
	(manual	SOA (linear)	30.94 (1, 5)	.861	.003
	and	SOA (quadratic)	71.09 (1, 5)	.934	<.001
	vocal)	Output modality * SOA (linear)	.95 (1, 5)	.160	.374
		Output modality *SOA (quadratic)	.05 (1, 5)	.009	.841
PE	Task 2	Output modality	16.25 (1, 5)	.765	.010
	(manual	SOA (linear)	.13 (1, 5)	.025	.736
	and	SOA (quadratic)	1.80 (1, 5)	.264	.238
	vocal)	Output modality * SOA (linear)	1.96 (1, 5)	.282	.220
		Output modality *SOA (quadratic)	.97 (1, 5)	.162	.370

Note. DV stands for dependent variable. If reported the kind of contrast is given in brackets for the respective effect. For each effect the *F*- value with the degrees of freedom in brackets, the partial eta square and the *p*-value is given.

The RT1: RT2 correlations of Group 4 as a function of SOA are displayed in Figure 5.5c and d for the manual and the vocal priority condition, respectively. Table 5.23 lists the results of the ANOVA on the correlation coefficients. The analysis revealed no effect of SOA on either priority condition.

Admittedly, the visual inspection of the time course of the correlations reveals a clear trend for increasing correlations with shorter SOAs. However, the size of the error bars report large standard errors (especially when comparing that to the data of Group 1 and 2).

Table 5.23. Summary of the ANOVA results testing the effect of SOA on the RT1-RT2 Fisher's Z transformed correlation coefficients for the vocal priority condition of Group 4 (S-R Non Standard, C-R Non Standard).

Task priority	Effect	*F*(df)	partial η^2	*p*
Vocal	SOA (linear)	(1, 5) 1.31	.208	.303
	SOA (quadratic)	.01 (1, 5)	.035	.687
Manual	SOA (linear)	.97 (1, 5)	.162	.371
	SOA (quadratic)	.46 (1, 5)	.084	.529

Table 5.24. Overview of the correlations between Task 1 and Task 2 RTs at different SOAs and for the different priority conditions of Group 4.

.Group	Manual priority				Vocal priority			
	SOA	*M* (*SD*)	*T* (df)	*p*	SOA	*M* (*SD*)	*T*(df)	*p*
4 (S-R Non	50	.48 (.28)	(5) 4.26	.008	50	.40 (.22)	(5) 4.41	.007
Standard,	150	.47 (.28)	(5) 3.82	.012	150	.33 (.20)	(5) 3.95	.011
C-R Non	250	.45 (.30)	(5) 4.02	.010	250	.30 (.22)	(5) 3.36	.020
Standard)	1000	.30 (.15)	(5) 4.90	.004	1000	.30 (.10)	(5) 7.26	.001

Note. Mean correlations with Standard Deviations (in brackets) as a function of SOA and priority; *T*-values for the test against zero are given with degrees of freedom and *p*-values.

Again, in both priority conditions SOA effects on Task 1 were observed. Therefore, also for Group 4 the response grouping hypothesis was tested by the inspection of IRIs at the 50 ms SOA (see Figure 5.7). The percentage of IRIs between -100 ms and +100 ms for the vocal priority condition is with 8% averaged across participants low. For the manual priority condition about 23% of the IRIs laid within this interval. With respect to this difference between the priority conditions, there was no consistent support for the response grouping strategy explaining the SOA effect on Task 1 for both priority conditions.

Table 5.25 summarizes the observed effects of SOA on RTs, PEs of Task 1 and Task 2 and on the RT1: RT2 correlations for Group 4. All predicted PRP effects were observed. However, the SOA effects on correlations did not reach the level of significance. Moreover, a SOA effect on each Task 1 was apparent that could not conclusively be explained by response grouping at short SOAs.

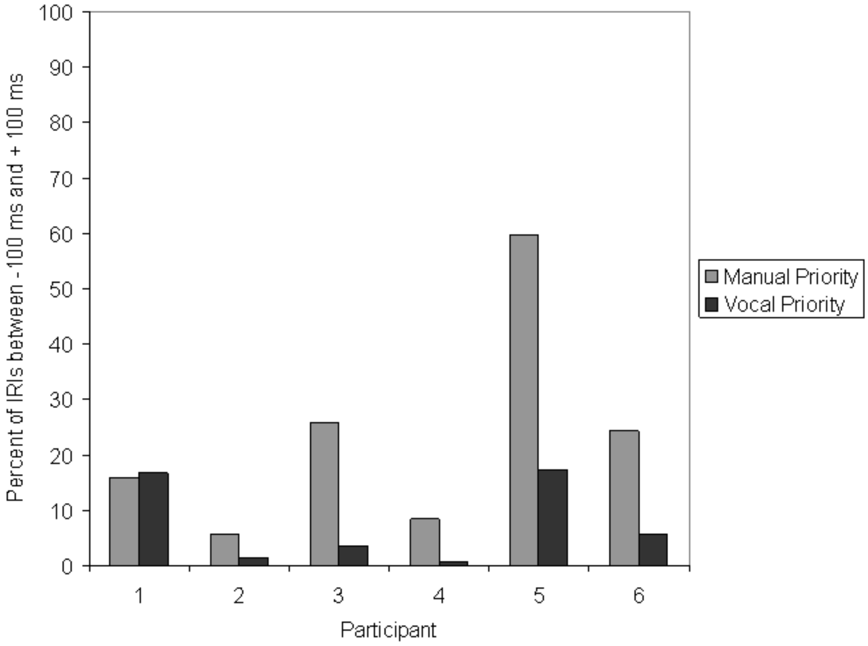

Figure 5.7. Histogram showing the proportion of inter-response intervals (IRIs) lying between -100 ms and +100 ms at the 50 ms SOA for each participant and priority condition of Group 4.

Table 5.25. Summary of SOA effects for each group and priority condition on RTs, PEs and RT1- RT2 correlations.

Group	Priority	Task 1		Task 2		RT1- RT2 correl.
		SOA→ RT	SOA→ PE	SOA→ RT	SOA→ PE	SOA→ r
1	Man	-	PRP (q)	- (IBL) - (LBN)	- (IBL) - (LBN)	- (IBL) - (LBN)
	Voc	-	-	-	-	-
2	Man	opp. PRP	PRP	PRP (q, IBL) - (LBN)	- (IBL) - (LBN)	- (IBL) - (LBN)
	Voc	PRP (q)	-	opp. PRP	opp. PRP	-
3	Man	PRP (l, q)	-	PRP (l, q)	PRP (l)	-
	Voc	PRP (l, q)	-	PRP (l, q)	-	PRP (l)
4	Man	PRP (l)	PRP (q)	PRP (l, q)	-	-
	Voc	PRP (l)	-	PRP (l, q)	-	-

Note. A dash represents a not significant effect of SOA. The l stands for a significant linear, a q for a significant quadratic trend. PRP stands for higher RTs, PEs and correlations for short than for long SOAs and opp. PRP means that RTs, PEs and correlations increased with increasing SOA. Man= Manual, Voc= vocal, IBL= inappropriate baseline, LBN= latent bottleneck, For the manual priority condition of Group 1 and 2 the IBL and LBN assumption make different predictions with respect to the SOA effect on RTs for Task 2 and RT1- RT2 correlations. Results are therefore listed separately with respective labels in brackets.

5.3. Discussion

In Experiment 4 the S-R and C-R modality-pairing groups that had practiced their respective two tasks in Experiment 3 were transferred to a PRP paradigm. In Experiment 3 crosstalk was found to be responsible for the differences in dual-task costs of the S-R and C-R modality-pairing groups. Low crosstalk in the C-R Standard pairing groups (Group 1 and 2) led to vanished costs after practice. Costs remained high when crosstalk was high as in the C-R Non Standard pairing groups (Group 3 and 4). The present PRP experiment examined whether a processing bottleneck was still present for the different S-R and C-R modality-pairing groups. Each group performed two PRP experiments, one for each possible task order.

C-R Standard groups

The parallel processing interpretation due to the vanished dual-task costs for Group 1 and 2 at the end of Experiment 3 could be challenged by assuming a latent bottleneck or an inappropriate single-task baseline that deflated dual-task costs. Both assumptions imply that the bottleneck was intact for the C-R Standard groups. Theses two possibilities were tested in the present experiment. The results were clear cut. There was no sign for a latent bottleneck for Group 1 or Group 2. For both groups none of the PRP effects in the manual or vocal priority condition that was predicted by the latent bottleneck assumption was observable. Furthermore, none of the correlations between the speed of Task 1 and Task 2 showed the predicted dependency on SOA. Hence, there is no support for assuming a latent bottleneck being responsible for the vanished dual-task costs for Group 1 and 2 in prior Experiment 3.

Likewise the support for the inappropriate baseline assumption is low. Since it makes the same predictions as the latent bottleneck account with respect to the vocal priority condition, the absent PRP for the RT of the manual Task 2 has to be repeatedly mentioned not supporting the bottleneck view. However, for the manual priority condition predictions from the latent bottleneck assumption in predicting a linear increase with decreasing SOA (not only a single increase for the negative SOA). This effect was not significant for Group 1 and 2. However, there was a significant quadratic SOA effect for Group 2. It amounted about 65ms from the shortest to the longest SOA. The effect was mainly due to a decrease in vocal RT2 for the longest SOA compared to the other. Assuming a bottleneck for this priority condition of Group 2 the correlations between RT1 and RT2 should also decrease with increasing SOA. This effect, however, was absent. Hence, there is no consistent evidence that this 65 ms effect in the manual priority condition of Group two is due to a response selection bottleneck. The effect seems rather to originate in a trade-off between the manual Task 1 and the vocal Task 2 since the manual Task 1 schowed a decrease in RTs with decreasing SOA.

Furthermore arguing against a bottleneck for the C-R Standard groups as predicted by the inappropriate baseline assumption, there was only one out of four predicted correlations (two for each group) between RT1 and RT2 showing a linear decrease with increasing SOA. This effect, which was observed for Group 1 in the manual priority condition, missed however the conventional level of significance. Moreover, no PRP effect was observable for this priority condition. Taken together, there is very low and moreover no consistent evidence for bottlenecks in Group 1 and 2.

There was one abnormal effect for the vocal Task 1 of Group 2, displaying an increase for RTs at short SOAs. However, it can be explained by assuming a trade-off between RTs of Task 1 and 2 since there was an inverse PRP effect on the manual task two in RTs and PEs for this priority condition and the correlations even approached significant negative values for the 200 ms SOA.

Altogether, both accounts predicting a bottleneck for Group 1 and 2 failed to adequately describe the present data. Hence, the results of the PRP experiment for the C-R Standard groups once more strongly confirms the view that the reduction in dual-task costs observed in Experiment 3 was accompanied by a switch from serial to parallel processing. This supports the view that with low representational overlap across tasks and consequent low crosstalk parallel processing can be induced with practice.

C-R Non Standard groups

For the C-R Non Standard groups the question is whether the dual-task interference observed in Experiment 3 can be attributed to crosstalk alone or to crosstalk and a functional bottleneck. In line with the bottleneck account PRP effects were found for both priority conditions of Group 3 and 4. Moreover, also SOA effects on RTs for Task 1 were observed, i.e. the increasing correlation with decreasing SOA. The effect on Task 1 is attributed to crosstalk between Task 1 and Task 2. There was no consistent evidence that this effect could be attributed to response grouping, which would be postulated by the traditional view of the bottleneck theory (assuming no crosstalk) to explain SOA effects on Task 1. Looking at the IRIs at the shortest SOA the percentage of IRIs that lay between -100 ms and 100 ms varied between 8% and 30% for the different task-priority conditions of Group 3 and 4. Admittedly, it seemed to be a strategy for isolated participants in one of the two priority conditions. This result is by far convincing in assuming the SOA effect on Task 1 being solely due to response grouping.

Mean correlations were numerically higher for the C-R Non Standard compared to the C-R Standard groups (except for Group 3 manual priority condition). This pattern suggests that there is greater crosstalk for the C-R Non Standard compared to the C-R Standard groups. Admittedly, this could also be due to the manual single-task RTs that were already longer for the C-R Non Standard compared to the C-R Standard pairing groups. Longer RTs go along with a greater variability than shorter RTs. Increased variability of the Task 1 central stage mean greater variability of the bottleneck stage. This results in an increased central deferment variance that is transferred to RT2. Hence, the difference in correlations could also be attributed to longer and hence more variable Task 1 RTs for the C-R Non Standard groups.

However, the correlation between RT1 and RT2 should be dependent on SOA according to the bottleneck idea. This effect could only be observed for Group 3 in the vocal priority condition. The SOA trend was not significant for the correlations of Group 3 in the manual priority condition. For the RT1- RT2 correlations of Group 4 the SOA dependency was also not significant. The question arises why the correlation was absent for the manual priority condition but present for the vocal priority condition. The vocal and the manual Task 1 of Group 3 yielded similar RTs with numerically similar variances; hence their potential to produce a bottleneck delay on the respective Task 2 should be the same. Admittedly it has to be said that at least for both task orders of Group 4 the trend of increasing correlations with shorter SOAs was visible. However, the error bars were large especially when comparing them to the correlation data of Group 1 and 2. Hence, the non significant SOA effect was perhaps due to low statistical power. Although results are less clear cut with respect to the RT1- RT2 correlations I think it is reasonable to assume that in addition to the crosstalk the bottleneck for the C-R Non Standard groups is still active after practice. There was a marked PRP effect for both priority conditions of the two groups and at least most of the correlations showed the increase with increasing SOA. Accepting crosstalk and the presence of a processing bottleneck the data of the C-R Non Standard groups would be in accordance with the model of Schubert et al. (Schubert, Fischer, & Stelzel, 2008) presented in the Introduction of Experiment 4.

Conclusion

The account for Schubert et al. cannot be applied to the data of all four groups. The model of Schubert et al. would always predict a bottleneck even in the absence of representational overlap and the consequent crosstalk. However, this was not observed for the C-R Standard groups. A comprehensive explanation of the present results has to integrate the vanished costs for the C-R Standard groups and the significant costs for the C-R Non Standard groups. A potential interpretation is to postulate that representational overlap across tasks and hence subsequent crosstalk induces a functional bottleneck. With minimal crosstalk, or in the absence of it, parallel processing is promoted. Thus, sequential processing would serve a functional purpose, i.e. to reduce errors associated with the crosstalk.

In the present experiment crosstalk was influenced by S-R and C-R modality-pairings. S-R pairings, however, did not influence the emergence of the bottleneck. Otherwise also Group 2, which had Standard C-R but Non Standard S-R pairings had to consistently show PRP effects in Experiment 4. This was not the case. Hence, only the crosstalk though C-R pairings determined whether parallel or serial processing was reached after practice. Crosstalk is the confusion between features across tasks. It is assumed to emerge when the activated features of each task have to be bound together. When there is confusion about which features have to be bound to which task, the binding of each task either takes longer to reverse the crosstalk. Another possibility would be to bind features of the two tasks serially to reduce errors. The first possibility is associated with parallel the second with serial processing of the two tasks. Crosstalk due to Non Standard S-R pairings was due to the representational overlap between less relevant stimulus features (coding the stimulus modality) and response features. Crosstalk due to Non Standard C-R modality-pairings was due to the representational overlap between the task relevant features of the stimulus and the response features. It can be speculated that the crosstalk produced by the Non Standard S-R pairings possibly was less severe than the crosstalk through C-R pairings, which induced serial processing. In this sense the central bottleneck can be understood as a binding process operating on features representing each task.

In line with this interpretation comes another prediction from the TEC. The theory postulates that a feature of one task is occupied through binding by the representation of this task, i.e. its event-code. Hence, it cannot be at the disposal of the representation of another event-code at the same time. The consequence for another task is that this task has to wait until the feature is available again. Indeed, on some trials identical spatial features had to be bound to different event codes at same time for the C-R Non Standard pairing groups. For the S-R Non Standard pairing groups representational overlap did not produce such a situation where identical features were part of both tasks. In Group 3 (see Table 4.1), for example, the spatial representation of the location of the tone (Task 2) could be the same as the spatial position of the manual key press task (Task 1). In this case the TEC would predict serial processing of the two tasks. Thus the transient binding of features would serve as a mechanistic principle for a functional bottleneck. In this sense Müsseler and Hommel (Müsseler & Hommel, 1997a) and Hommel and Müsseler (Hommel & Müsseler, 2006) found that the identification of a left- or right-pointing arrowhead is impaired when it is displayed while planning and executing a spatially compatible left or right key press. This is because both tasks operate on the same features. These features are bound into the event-code of the manual task and hence are less available for perceptual processing. However, the competition for identical features was only present on trials with cross-task compatibility, i.e. not on every trial. Hence, feature occupation cannot fully explain the emergence of the bottleneck for the C-R Non Standard groups.

Taken together, the results of Experiments 3 and 4 showed that the process of response selection is not an amodal process as the prominent dual-tasks theories as EPIC and the bottleneck theory postulate. Response selection is dependent on the representational codes that have to be bound together to a task. This is especially important for dual-task situations, where interactions across task representations may arise. Moreover, it could be shown that the bottleneck is not inevitable. The vanished dual-task costs of the C-R Standard pairing groups found in Experiment 3 and 4 support a parallel processing view. Low crosstalk due to low representational overlap across tasks allows their simultaneous processing. Serial processing could be induced by the structural limitation of feature occupation or could serve the functional basis of reducing crosstalk related errors or an interplay of both. Future research has to answer the question for the specific mechanisms of the crosstalk. What are the specific conditions when it leads to serial processing and how does practice cause a qualitative change in performance from serial to parallel processing when crosstalk is low?

6. General Discussion

6.1. An integrated view of dual-task costs

The aim of the thesis was to explore limiting factors of parallel processing in dual-task situations. Experiments 1 and 2 examined the role of the S-R compatibility of tasks on their dual-task performance. Experiments 3 and 4 addressed the question of modality dependent central processing. In the following I summarize and review the results of the four experiments. An alternative account to the traditional view of response selection as in Pashler's bottleneck theory (1984; Pashler, 1994a) is discussed.

6.1.1. S-R compatibility

In Experiments 1 and 2 the effect of S-R compatibility on parallel processing was examined with two continuous memory updating tasks. The results showed that the parallel processing ability of two tasks was reduced when both tasks contain low S-R compatibility compared to a task combination where at least one task contains high S-R compatibility. This result could not be explained by higher single-task RTs for the former compared to the latter task combination. The dual-tasking results of Experiment 1 were compared to the subgroup of young participants in Göthe et al. and Oberauer and Kliegl (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) and found a difference in dual-task costs (with higher costs for the less compatible task combination of Experiment 1) despite equal single-task RTs for the two task combinations. Experiment 2 could replicate this result for a within-experiment manipulation. The difference in dual-task costs was attributed to higher potential of crosstalk between top-down control signals needed for the two non compatible S-R mapping processes. Nevertheless, the results of one of the participants showed that parallel processing was possible for two tasks both containing non compatible S-R mappings (Experiment 1).

6.1.2. Modality pairings

Experiments 3 and 4 examined the effects of modality pairings on dual-task interference. In earlier experiments dual-task costs were found to be higher when two tasks with Non Standard modality-pairings (a visual-vocal and an auditory-manual task) are combined than when both tasks contain Standard modality-pairings (a visual-manual and an auditory-vocal task). This could be attributed to differences in single-task performance (Hazeltine & Ruthruff, 2006; Hazeltine, Ruthruff, & Remington, 2006; Ruthruff, Hazeltine, & Remington, 2006; Shaffer, 1975; Stelzel, Schumacher, Schubert, & D'Esposito, 2005). Examining this effect four different modality-pairing groups practiced their two tasks within an SPP (Exp. 3) and were subsequently transferred with their tasks to a PRP (Exp. 4). Experiment 3 asked whether the modality-pairing effect on dual-task costs can be attributed to between-task crosstalk. This crosstalk is due to overlap between stimulus and response representations across tasks for the Non Standard pairings. Overlap can be present due to the assumption that stimuli and responses are mapped within a common representational space (Prinz, 1990). When two tasks with Non Standard modality-pairings are combined representations of both tasks rely on verbal and spatial features. This gives way to crosstalk between the tasks. Mutual crosstalk leads to confusion of features, which hampers dual-task performance, i.e. to correctly define which feature belongs to which task. For Standard modality-pairings verbal and spatial features are part of different tasks, i.e. the S and R representations of one task relies only on spatial features and the other task only on verbal features. Hence, in the Standard modality-pairing case the overlap and the resulting confusion are low. In Experiment 3 S-R and C-R modality-pairings were varied across the four groups being either Standard or Non Standard in nature. Standard S-R modality-pairings are visual-manual and auditory-vocal input-output modality-pairings. They become Non Standard when the modality-pairings are crossed (auditory-manual and visual-vocal). Standard C-R modality-pairings are spatial-manual and verbal/sonic-vocal central-output modality-pairings. They also become Non Standard when the modality-pairings are crossed (verbal/sonic-manual and spatial-vocal).

The nature of the C-R pairings contained the overlap between the task-relevant stimulus features and the response representation. The overlap due to C-R modality-pairings was in former experiments supposed to be responsible for the observed effects on dual-task costs. This could be disentangled from the overlap due to S-R pairings with the particular task design of Experiments 3 and 4. S-R pairings contained the overlap between less relevant stimulus features and the response. The results clearly showed that the effects of S-R and C-R pairings on dual-task costs were higher than one would predict according to their effects on single-task performance. As predicted the C-R pairing effect was stronger than the S-R pairings since the C-R pairings coded the overlap between task relevant features across task representations. Moreover, the C-R Standard groups (Group 1 and 2) yielded vanished dual-task costs in RTs after practice with only small costs in errors for Group 2. In contrast for the C-R Non Standard groups (Group 3 and 4) significant dual-task slowing remained. In sum the results of Experiment 3 match the predictions of the crosstalk assumption, which postulates representational overlap as a cause of modality-pairing effects on dual-task costs.

Experiment 4 asked whether the minimal to zero interference found within the SPP for the C-R Standard groups could be replicated within a PRP paradigm. A further question was whether crosstalk was the only source of interference for the C-R Non Standard groups or whether in addition to the crosstalk a bottleneck was present. The results over all confirm the vanished dual-task costs for the C-R Standard groups. For the C-R Non Standard groups the results were in between strong support and strong rejection with respect to a bottleneck that was present in addition to the crosstalk. Whereas PRP effect could be observed for each task order for the C-R Non Standard groups, the SOA effect on the RT1-RT2 correlations missed significance. The visual inspection of the correlation data however, revealed a SOA effect showing increasing correlations with increasing SOA that was present for most of the PRP experiments of the C-R Non Standard groups. Though, the standard error of the mean was high supposing that the statistical power was too low to detect the effect. Therefore the data of the C-R Non Standard groups was interpreted in the way that a bottleneck in addition to the crosstalk was present. The strong crosstalk possibly induced the bottleneck to reduce the potential of confusion across tasks and hence errors.

Taken together, the outcome of Experiments 3 and 4 points out that reported modality-pairing effects on dual-task costs originate in between-task crosstalk due to representational overlap. These results show that the process of response selection is not independent of its content. Interactions may emerge since task contents overlap. Moreover, keeping the potential for interaction low, response selection of two tasks can run in parallel after practice. Evidence that with crosstalk between two tasks their response selection processes might still be applied serially after practice was not without doubt but a very reasonable interpretation of the data.

6.1.3. Practice

One characteristic that connects the results of the experiments of the thesis is the fact that for all practice played a major role for the reduction of dual-task costs. Generally, without practice dual-task costs were observed. Considerable task specific dual-task practice minimized interference. Whereas some theorists argue that this is just a quantitative reduction (Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Van Selst, Johnston, & Remington, 2006) several results of the present thesis provide strong evidence that this reduction was accompanied by a qualitative change in processing from serial to parallel processing for certain task combinations. Practice was formulated as one determinant for inducing parallel processing in the EPIC model (Meyer & Kieras, 1997a). However, the specific mechanisms that lead to the achievement of parallel processing with practice are still unknown.

Speculating on that Oberauer and Kliegl (Oberauer & Kliegl, 2004) formulated that practice reduces the influence of the top-down control signals on task implementation. To the degree the implementation of S-R mappings becomes autonomous of their control signals the tasks can be processed in parallel because the potential of supervision-based crosstalk and therefore the error potential decreased.

However, future studies may shed light on the question. For example, it is unclear whether there are transfer effects of the parallel processing ability. When parallel processing is acquired for a task combination it is thinkable that similar task combinations can also be processed in parallel with further ado. At least it is thinkable that for parallel processors compared to persons starting at serial processing the parallel processing for similar task combinations could be reached faster. When there are transfer effects it would be interesting to know their limits. How similar task combinations have be to make use of transfer effects? Or once acquired parallel processing for one task combination is there some kind of a general ease for all other task combinations with parallel processing potential?

Another question concerns the formation of other processing circuits due to a change in the processing strategy. When dual-task costs vanished with practice, were the same neural pathways recruited as before practice or did extensive practice lead to the construction of alternate neural pathways. Moreover, are task combinations that produce minimal to zero dual-task costs at the end of practice already recognizable at the beginning? Answering these question would help to understand better the functions of our information processing architecture.

6.1.4. Interindividual differences

The aim of the present thesis was not to test interindividual differences in the ability to process two tasks in parallel. However, Experiment 1 and 2 inspected the data of individual practice trajectories. The results suggest that interindividual differences play a role for the prediction of dual-task interference. In Experiment 1 there were dramatic differences in the residual dual-task costs after practice among the nine tested participants. Only one participant was able to vanish dual-task costs and was classified as a parallel processor. Moreover, also in Experiment 2 there was one parallel processor in the compatible spatial mapping group whereas the other eleven participants of this group showed serial processing.

How dual-task situations are managed does not only depend on the characteristics of the tasks but also on the characteristics of the person. The EPIC model implemented personal preferences for cautious or daring task scheduling (Meyer et al., 1995). Participants differ in their more or less general strategy of how to manage situations with parallel processing potential. This individual difference in the task scheduling strategy emerges as practice progresses. However, trying to get a deep understanding of the information processing architecture further factors promoting individual differences have to be explored. Speculating on that the susceptibility to interference might be one candidate. Simply put susceptibility or resistance to interference refers to the ability to ignore or inhibit irrelevant information while effectively activate relevant information. In a dual-task situation one has two relevant tasks that had to be activated. Thus the inhibition of irrelevant information of one task would be disastrous since it would mean to inhibit relevant information of the other task. Nevertheless, there is need to keep both task representations apart and keep interference as low as possible.

6.1.5. The response selection bottleneck

The model of a response selection bottleneck dominated the dual-task research in the 80th and 90th. Several results, however, have recently questioned its scope. There is a small but growing number of studies using different task combinations showing vanished dual-task costs (Göthe, Oberauer, & Kliegl, 2007; Hazeltine, Teague, & Ivry, 2002; Oberauer & Kliegl, 2004; Ruthruff, Hazeltine, & Remington, 2006; Schumacher et al., 2001). However, the bottleneck claimed to be ubiquitous when two tasks with central processing had to be processed at the same time. Moreover, if costs are present they do not depend on central duration of Task 1 as predicted by a core assumption of the bottleneck framework. However, there were several exceptions to this prediction.

Hazeltine and Hazeltine and colleguages (Hazeltine & Ruthruff, 2006; Hazeltine, Ruthruff, & Remington, 2006) observed differential dual-task costs for different S-R modality-pairing groups that could not be attributed to differences in single-task performances. Moreover, it could be shown that despite costs the PRP effect and hence the bottleneck for different S-R modality-pairing groups was absent after practice (Ruthruff, Hazeltine, & Remington, 2006).

Manipulating crosstalk between two tasks Koch (2009) could show differential dual-task costs for groups with high and low crosstalk between their tasks. Koch manipulated crosstalk between two tasks by varying the spatial response code overlap between a vocal naming task and a manual key press tasks. He found that for a high crosstalk group (high spatial overlap) dual-task costs were higher than for the low crosstalk group (low spatial overlap). This difference could not be explained by different single-task performances of the two groups. Koch furthermore observed low and sometimes vanished dual-task costs for the low crosstalk group.

Furthermore, the already cited backward compatibility effect (Hommel, 1998a) describes a compatibility effect of Task 2 response to Task 1 stimulus at short SOA. At short SOA, however, the response selection process for Task 2 could not have taken place since it has to wait for the completion of Task 1. Hence, according to the bottleneck model there should not be any compatibility effects of Task 2 onto Task 1 at short SOA.

Likewise, the present thesis examined several discrepancies to the predictions of the central bottleneck theory. In Experiments 3 and 4 vanished costs were documented for both C-R Standard groups. The empirical evidence for parallel processing in Experiments 1 and 2 is weaker, however also in Experiments 1 and 2 vanished dual-task costs could be shown in each experiment for at least one participant. Hence, the present thesis showed the disappearance of a bottleneck with practice for different task combinations and experimental paradigms. Taken together, the present thesis could show that the central bottleneck is not as ubiquitous as it has been claimed by its proponents (Pashler, 1994a).

Moreover, several instances where the amount of interference did not depend on single-task performance were found in the present thesis. Experiment 2 revealed equal single-task performances of the verbal and the spatial memory updating tasks of two groups differing only in the S-R compatibility of the spatial task. Dual-task costs were, however, higher for the incompatible spatial mapping group compared to the compatible spatial mapping group. Likewise, the between experiment comparison of Experiment 1 and two earlier experiments using an identical verbal task and a spatial tasks with a higher S-R compatibility than in Experiment 1 (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004) revealed differential dual-task costs despite equal single-task performances. Finally, Experiment 3 and 4 showed S-R and C-R pairings influencing dual-task costs stronger than single-task RTs.

Which conclusions have to be drawn from these results with respect to the bottleneck model? One theoretical consequence, of course, would be to adapt the bottleneck model to the observed contradictory results. Schubert et al (Schubert, Fischer, & Stelzel, 2008), as explained in the Introduction of Experiment 4, reformulated the bottleneck model to explain between-task crosstalk, e.g. responsible for the backward compatibility effect but also applicable to the observed S-R and C-R pairing effects in Experiment 3 and 4. Schubert et al. thereby postulate central interactions between tasks, however, still keeping a serial and amodal processing bottleneck. The authors assume that S-R translation is driven by automatic activation and response selection, with the former taking place in parallel and the latter working serially in dual-task situations (Hommel, 1998a). The activation of stimuli and responses for Task 1 and 2 at short SOAs causes crosstalk between them when there is informational overlap (e.g. spatial correspondence) between task representations. The pre-activation of Task 2, however is completely reset before it enters the bottleneck and therefore has no direct influence on its duration. Hence, the bottleneck assumption of non interacting central processes at least at response selection is saved with this account. Keeping the bottleneck active in addition to crosstalk therefore would predict dual-task interference to be higher than one would predict on the basis of single-task performance. Hence, assuming crosstalk to take place together with a functional bottleneck could explain the differential effects of S-R and C-R pairings on single-task and dual-task performance. However, Schubert et al. would predict a bottleneck to be active even in the absence of crosstalk, which was not observed for the C-R Standard groups in Experiment 3 and 4.

The adaption of the bottleneck model to the results of Experiment 1 and 2 also fails even if only because both experiments revealed parallel processors. Irrespective of the parallel processors, the differences observed in dual-task costs that were not attributable to single-task differences could be explained by simply postulating that crosstalk between executive processes is part of the central processing bottleneck. An additional task set reconfiguration stage after S-R selection of Task 1 suppressing Task 1 task set and activating Task 2 task set is thinkable. This assumption is reasonable, however, reduces the simplicity in predicting costs on the basis of central processing durations.

Taken together, the question consequently is whether the necessary adaptation of the bottleneck model especially to the results of Experiment 3 and 4 does not hurt its central assumptions, i.e. the strict amodality of the response selection process and its ubiquity in situations where S-R selection processes have to be executed at the same time.

6.2. Response selection revised: An alternative information processing account

Questioning the bottleneck framework does not mean to give up the assumption of serial processing in the sense of a functional bottleneck. However, given the present results, the information processing framework underlying the response selection bottleneck as Pashler adopted it has to be reconsidered. As already mentioned in Experiment 3 and 4 the theory of event coding (Hommel, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001) represents an alternative account to look at dual-task processing. As described, the TEC assumes that representations of stimuli and responses are activated and integrated into a task through transient binding. Representations of stimuli and responses consist of features, which share a common medium (Prinz, 1990). That means that the representations of a visual left-pointing arrow and of a left manual key press base on the same features representing the location “left”. This representational format entails interactions across tasks in a dual-task situation.

In this sense response selection is seen a representation-specific process since the specific features have to be bound together to a task (event code). Furthermore, the processing aspect within the TEC, i.e. the selection through transient binding of features provides a functional principle for the serial processing bottleneck. When the features of two tasks are activated, the two binding processes can conflict. Conflicts can arise due to confusion of features (cf. the "dual-task binding problem", Logan & Gordon, 2001), i.e. to bind stimulus and response features which do not belong together according to the task context. The default setting of the cognitive system therefore, is to bind features of two tasks serially to avoid errors. However, when the system learns with practice that the error potential is low the two binding processes can be applied in parallel. Hence, for two tasks with low representational overlap across tasks, low crosstalk arises and parallel processing can be reached.

In Experiment 3 and 4 it could be shown, that confusion or crosstalk arises when features of two tasks originate from the same representational domain (Non Standard modality-pairings). For the C-R Non Standard groups the binding processes suffered much more crosstalk than for the C-R Standard groups, where crosstalk due to representational overlap was minimal or even absent. Although, for all groups costs were significant at the beginning only the latter groups showed parallel processing after practice.

For the TEC a special case establishes when the features of the two tasks not only stem from the same broad domain but are identical. The specific prediction of the TEC is that when two binding processes have to acess an identical feature, they cannot be processed in parallel. Once a feature is bound to represent task A, it is not or at least less available for coding task B as long as task A has not been performed. This has already been demonstrated for a combination of a sensorimotor and a perceptual identification task (Müsseler & Hommel, 1997a, 1997b). Planning manual left-right key pressing actions impaired the identification of spatially corresponding arrows. This was not restricted to the execution phase of the response but also occurs while the response is being planned and held in preparation (Wühr & Müsseler, 2001).

This feature occupation account could be an alternative interpretation to the mere serial processing assumption of the C-R Non Standard groups. For the C-R Non Standard groups, on compatible trials the two tasks shared the spatial feature left or right (see Table

4.1), which was part of the visual stimulus of one task and the manual response of the other task. Hence, according to the TEC at least in these trials the two response selection processes could not have been processed in parallel. However, there were also incompatible trials in which the features that had to be bound to each task still came from the spatial domain but were not identical. On those trials there is no need to compete for a certain feature; nevertheless, crosstalk is still assumed. Perhaps for the C-R Non Standard groups not crosstalk per se but more specifically the need to bind identical features on compatible trials lead to a serial processing mode. However, it is a question for future research to explore in much detail the specific mechanisms of crosstalk and feature occupation that make parallel processing less likely or even prevent it.

The binding of features is commonly focused in visual perception. Postulating the binding of features as the basic mechanism for a serial processing bottleneck, however, also enables the TEC to explain interference effects of perceptual tasks on sensorimotor tasks. Such effects are not in accordance with the traditional bottleneck account were, however, frequently observed (Jolicoeur & Dell'Acqua, 1998; Müsseler & Hommel, 1997a, 1997b). A perceptual task does not require a central process which translates the stimulus into a motor response since it is defined by the absence of a motor response. Central interference, however, should only be apparent when both tasks require the bottleneck mechanism. Moreover, Pashler took the absence of such interference effects as evidence for the central bottleneck (Pashler, 1993). However, there are counterexamples as already seen for the effect of action planning on the identification of arrow directions (Müsseler & Hommel, 1997a, 1997b). Moreover, Jolicoeur and Dell'Aqua (1998) found in several experiments that interference emerged when a visual encoding and an two-choice sensorimotor task were combined. The subjects, for example, had to identify and memorize a briefly presented backward masked symbol (a letter or a digit) for recall at the end of the trial. After a variable SOA an auditory stimulus, either a high or a low pitch tone had to be answered by pressing a left or a right key. The RTs for the auditory tasks were significantly higher for short compared to longer SOAs. The authors assumed a capacity limited processing mechanism for the consolidation of visual information in short-term memory that interferes with the response selection of the auditory task. Thereby, they kept the bottleneck account by postulating that a perceptual process requires the central mechanism. Seen from the TEC the emergence of interference between a perception and a sensorimotor task are due to two binding processes taking place serially- one for the consolidation of the percept in short-term memory and one for the auditory-manual task. In this sense whenever the binding process for the consolidation in and retrieval from working memory is needed a functional bottleneck emerges.

Binding of features happens according to the predefined task affordances, task-sets, and internal goals. Executive processes supervise the binding processes and influence their scheduling. Experiment 1 and 2 showed that there are good reasons to assume also confusion across tasks on a higher order level next to the content-based, i.e. representational crosstalk. However, the TEC does not operate on this conception regarding supervision-based crosstalk.

To summarize, the conception of a functional bottleneck as the binding of features would be representation specific and not amodal as traditionally formulated. Moreover, under favorable conditions it can be overcome. Such a conception would be in accordance with the present data.

6.3. Conclusion

In the present thesis three different dual-task paradigms were used to examine dual-task interference: the continuous memory updating task, the SPP and the PRP paradigm. Despite their diversity and the diversity of the task combinations used, there is accordance that after practice dual-task processing without costs is possible. Admittedly, this result was not the dominating finding. The question put at the beginning of the thesis was why significant dual-task costs emerge so numerous in comparison to the few exceptions showing minimal to vanished costs when performing two tasks. Perhaps the answer lies not in the impossibility but in the possibility of parallelism in processing of two tasks. This parallelism gives way to unwanted interactions, which on their part allow for task errors. Doing two things at once, however, producing erroneous results would entail to do things at once at least twice. From this viewpoint, an interposed processing delay in one task reducing the potential of confusion would at first save accuracy and with this also time.

A theoretical conclusion that can be drawn from the present results is that the concept of response selection has to be altered. Response selection was long seen as a unitary process, i.e one amodal central process that is applied in most if not all sensorimotor tasks. However, response selection seems to be more complex than originally proposed and at the same time also more flexible. It seems to be driven by multiple processes. The activation of features constituting the respective stimulus and its response, their transient binding to a task and executive processes supervising their selection according to the task affordances were discussed to be part of response selection. Whereas activation takes place in parallel for two tasks, the binding is mostly applied serially. There are however, factors promoting that with practice binding can be applied in parallel. Among them are low representational overlap between tasks and high S-R compatibility of at least one task. These conditions lead to less crosstalk and hence less confusion errors between tasks. Crosstalk can take place at the representational and at the executive level.

Whereas the theoretical implications lead to a positive view in the sense of possible parallel processing the practical implications are nevertheless sobering. In everyday life there are many multi-tasking possibilities: Checking SMS messages while talking to a friend, surfing the net during watching TV, checking mails while talking on the phone. In most of these and other dual-task situations the conditions are not favoring in the sense of strong crosstalk, which makes them highly error-prone. Hence when precision is required, it would be beneficial to stay or to become a single-tasking person.

In professional life, however, dual-task situations can be optimized. This is especially necessary for highly responsible positions where accurate acting has to take place very fast. Man-machine interfaces for aircraft controllers and pilot, for example, have to be designed in such a way that two tasks that possibly have to be processed together are maximal dissimilar and highly S-R compatible. Moreover, it is essential to practice simultaneous processing, because dual tasking is even harder the less practiced the tasks are. In this sense, even it is possible to process two tasks in parallel efficient dual tasking is limited. Hence, being a single-tasking person in a multi-tasking world can be advantageous in many cases.

7. Literature

Allen, P. A., Lien, M.-C., Murphy, Martin D., Sanders, R. E., & McCann, R. S. (2002). Age differences in overlapping-task performance: Evidence for efficient parallel processing in older adults. *Psychology and Aging, 17*(3), 505-519.

Allport, D. A., Antonis, B., & Reynolds, P. (1972). On the division of attention: A disproof of the single channel hypothesis. *Quaterly Journal of Experimental Psychology, 24*, 225-235.

Baddeley, A. D. (1986). *Working memory*. Oxford, England: Clarendon Press.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423.

Bakeman, R., & McArthur, D. (1996). Picturing repeated measures: Comments on Loftus, Morrison, and others. *Behavior Research Methods, Instruments, & Cognition, 28*(4), 584-589.

Brambosch, A. (2003). *Auf der Suche nach Grenzen humaner kognitiver Simultanverarbeitung.* University of Potsdam, Potsdam.

Broadbent, D. E. (1958). *Perception and communication*. New York: Oxford University Press.

Bruce, C., Desimone, R., & Gross, C. G. (1981). Visual properties of neurons in a polysensory area in superior temporal sulcus of the macaque. *Journal of Neurophysiology, 46*(2), 369-384.

Carrier, L. M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning Memory and Cognition, 21*(5), 1339-1348.

De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 965-980.

De Jong, R. (1995). The role of preparation in overlapping-task performance. *Quaterly Journal of Experimental Psychology A, 48*(1), 2-25.

De Jong, R. (2000). An intention-activation account of residual switch costs. In S. Monsell & J. Driver (Eds.), *Control of cognitive Processes: Attention and Performance XVIII*. Cambridge, MA: MIT Press.

Duncan, J. (1986). Disorganisation of behaviour after frontal lobe damage *Cognitive Neuropsychology, 3*(3), 271-290.

Fitts, P. M., & Seeger, C. M. (1983). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology, 46*, 199-210.

Gopher, D., & Navon, D. (1980). How is performance limited: Testing the notion of central capacity *Acta Psychologica, 46*(3), 161-180.

Göthe, K., Oberauer, K., & Kliegl, R. (2007). Age differences in dual-task performance after practice. *Psychology and Aging, 22*(3), 596-606.

Greenwald, A. G., & Schulman, H. G. (1973). On doing two things at once: II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology, 101*, 70-76.

Hazeltine, E., & Ruthruff, E. (2006). Modality pairing effects and the response selection bottleneck. *Psychological Research, 70*, 504-513.

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology, 52*, 291-345.

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance, 28*(3), 527-545.

Henson, R. (2001). Neural working memory. In J. Andrade (Ed.), *Working memory in perspective* (pp. 151–173). Hove, East Sussex, England: Psychology Press.

Hirst, W., Spelke, E., Reaves, C., Caharack, G., & Neisser, U. (1980). Dividing attentionwithout alternation or automaticity. *Journal of Experimental Psychology: General, 109*, 98-117.
Hommel, B. (1993a). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research, 55*, 270-279.
Hommel, B. (1997). Toward an action-concept model of stimulus-response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 281-320). Amsterdam: North-Holland.
Hommel, B. (1998a). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24*(5), 1368-1384.
Hommel, B. (1998b). Event files: Evidence for automatic integration of stimulus-response episides. *Visual Cognition, 5*((1/ 2)), 183-216.
Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494-500.
Hommel, B., & Müsseler, J. (2006). Action-feature integration blinds to feature-overlapping perceptual events: Evidence from manual and vocal actions. *The Quaterly Journal of Experimental Psychology, 59*(3), 509-523.
Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and brain sciences, 24*, 849-937.
Jolicoeur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36*, 138-202.
Jolicoeur, P., & Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. *Psychological Research, 62*, 154-164.
Jonides, J., Reuter-Lorenz, P. A., Smith, E. E., Awh, E., Barnes, L. L., Drain, M., et al. (1996). Verbal and spatial working memory in humans. In D. Medin (Ed.), *Psychology of Learning and Motivation* (Vol. 34, pp. 43–88).
Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.
Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *Quaterly Journal of Experimental Psychology, 20*, 167-178.
Koch, I. (2009). The role of crosstalk in dual-task performance: evidence from manipulating response-code overlap. *Psychological Research, 73*, 417–424.
Koelsch, S., Gunter, T. C., von Cramon, D. Y., Zysset, S., Lohrmann, G., & Friederici, A. D. (2002). Bach speaks: A cortical "language-network" serves the processing of music. *NeuroImage, 17*, 956-966.
Kornblum, S. (1992). Dimensional overlap and dimensional relevance in stimulus-response and stimulus-stimulus compatibility. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in Motor Behavior II*: Elsevier Science Publishers B.V.
Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility- A model and taxonomy. *Psychological Review, 97*(2), 253-270.
Levy, J., & Pashler, H. (2001). Is dual-task slowing instruction dependent? *Journal of Experimental Psychology: Human Perception and Performance, 27*(4), 862-869.
Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2006). Attentional limitations in doing two tasks at once: The search for exceptions. *Current Directions in Psychological Science, 15*(2), 89-93.
Lien, M.-C., Ruthruff, E., & Proctor, R. W. (2005). Dual-task performance with ideomotor-compatible tasks: Is the central processing bottleneck intact, bypassed, or shifted in

locus? *Journal of Experimental Psychology: Human Perception and Performance, 31*(1), 122-144.
Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*(2), 393-434.
Logie, R. H. (1995). *Visuo-spatial working memory*. Hillsdale, NJ: Erlbaum.
McCann, R., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference *Journal of Experimental Psychology: Human Perception and Performance, 18*(2), 471-484.
McLeod, P. (1977). Parallel processing and the psychological refractory period. *Acta Psychologica, 41*, 381-396.
Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104*(1), 3-65.
Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104*(4), 749-791.
Meyer, D. E., Kieras, D. E., Lauber, E. J., Schumacher, E. H., Glass, J. M., Zurbriggen, E., et al. (1995). Adaptive executive control: Flexible multi-task performance without pervasive immutable response-selection bottlenecks. *Acta Psychologica, 90*, 163-190.
Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*(3), 134-140.
Müsseler, J., & Hommel, B. (1997a). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 861-872.
Müsseler, J., & Hommel, B. (1997b). Detecting and identifying response-compatible stimuli. *Psychonomic Bulletin & Review, 4*, 125-129.
Navon, D. (1984). Resources–a theoretical soup stone? *Psychological Review, 91*(2), 216-234.
Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review, 86*, 254-284.
Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*, 193-251.
Nino, R. S., & Rickard, T. C. (2003). Practice effects on two mwmory retrievals from a single cue. *Journal of Experimental Psychology: Learning Memory and Cognition, 29*(3), 373-388.
Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1-18). New York: Plenum.
Nowak, L. G., Munk, M. H., Girard, P., & Bullier, J. (1995). Visual latencies in areas V1 and V2 of the macaque monkey. *Visual Neuroscience, 12*(2), 371-384.
Oberauer, K., & Kliegl, R. (2001). Beyond resources: Formal models of complexity effects and age differences in working memory. *European Journal of Cognitive Psychology, 13*(1/2), 187–216.
Oberauer, K., & Kliegl, R. (2004). Simultaneous cognitive operations in working memory after dual-task practice. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 689-707.
Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10*(3), 258-377.
Pashler, H. (1993). Dual-task interference and elementary mental mechanisms. In D. E. Meyer & S. Kornblum (Eds.), *Attention and Performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 245-264). Cambridge, USA: MIT Press.

Pashler, H. (1994a). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*(2), 220-244.
Pashler, H. (1994b). Graded capacity sharing in dual-task interference? *Journal of Experimental Psychology: Human Perception and Performance, 20*, 330-342.
Pashler, H. (1998). *The psychology of attention*. Cambridge,MA: MIT Press.
Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *The Quaterly Journal of Experimental Psychology, 41 A*(1), 19-45.
Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance (pp. 155–189). Hove, UK: Psychology Press. In H. Pashler (Ed.), *Attention* (pp. 155-189). Hove, UK: Psychology Press.
Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relations between perception and action* (pp. 167-201). Berlin: Germany, Springer.
Proctor, R. W., & Lu, C.-H. (1999). Processing irrelevant location information: Practice and transfer effects in choice-reaction tasks. *Memory & Cognition, 27*(1), 63-77.
Recanzone, G. H., Guard, D. C., & Phan, M. L. (2000). Frequency and intensity response properties of single neurons in the auditory cortex of the behaving macaque monkey. *Journal of Neurophysiology, 83*(4), 2315-2331.
Rogers, R., & Monsell, S. (1995). The cost of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207-231.
Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 763-797.
Ruthruff, E., Hazeltine, E., & Remington, R. W. (2006). What causes residual dual-task interference after practice? *Psychological Research, 70*(6), 494-503.
Ruthruff, E., Johnston, J. C., & Van Selst, M. (2001). Why practice reduces dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 3-21.
Ruthruff, E., Johnston, J. C., Van Selst, M., Whitsell, S., & Remington, R. (2003). Vanishing dual-task interference after practice: has the bottleneck been eliminated or is it merely latent? *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 280-289.
Ruthruff, E., Pashler, H., & Klaassen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review, 8*(1), 73-80.
Ruthruff, E., Van Selst, M., Johnston, J. C., & Remington, R. (2006). How does practice reduce dual-task interference: Integration, automatization, or just stage-shortening? *Psychological Research, 70*(2), 125-142.
Salthouse, T. A. (1988). Resource-reduction interpretations of cognitive aging. *Developmental Review, 8*(3), 238-272.
Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34*(2), 376-397.
Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., et al. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science, 12*(2), 101-108.
Shaffer, L. H. (1975). Multiple attention in continuous verbal tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and Performance V* (pp. 157-167). New York: Academic Press.

Simon, J. R. (1990). The effects of an irrelevant directional cue on human information processing. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus-response compatibility: An integrated perspective*. Amsterdam: Elsevier.

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2005). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychological Research, 70*(6), 514-525.

Sternberg, S. (1969). On the discovery of processing stages: Some extentions of Donder's method. *Acta Psychologica, 30*, 276-315.

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology, 14*, 1-36.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 3-18.

Tombu, M., & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology: Human Perception and Performance, 30*(5), 795-810.

Van Selst, M., & Jolicoeur, P. (1994). Can mental rotation occur before the dual-task bottleneck? *Journal of Experimental Psychology: Human Perception and Performance, 20*(4), 905-921.

Van Selst, M., Ruthruff, E., & Johnston, J. C. (1999). Can practice eliminate the psychological refractory period effect? *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1268-1283.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance- a review and a theory. *British Journal of Psychology, 43*, 2-19.

Welford, A. T. (1980). The single-channel hypothesis. In A. T. Welford (Ed.), *Reaction time* (pp. 215-252). London: Academic Press.

Wickens, C. D. (1980). The structure of attentional resources. In R. Nickerson & R. Pew (Eds.), *Attention and Performance VII* (pp. 239-257). Hillsdale N J: Erlbaum.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman, J. Beaty & R. Davies (Eds.), *Varieties of attention*. New York: Wiley.

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource comptetition between modalities of input, central processing and output. *Human Factors, 25*(2), 227-248.

Wühr, P., & Müsseler, J. (2001). Time course of blindness to response compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 27*(5), 1260-1270.

8. Appendices

8.1. Appendix A: Serial processors of Experiment 2.

Table A1. Mean RTs, PEs and test statistics for the last three training blocks of the serial processors of Experiment 2. *SD*s are given in brackets for the RTS and the PEs.

Group	ID	Session	RT			PE		
			Max (seq)	Sim	*T*(df)/	Seq	Sim	χ^2
Comp.	B	10	458 (59)	557 (95)	-5.49 (65.47)*	2.50 (11.04)	0	2.05
		11	416 (52)	464 (43)	-4.43 (76)*	1.25 (7.91)	2.50 (15.81)	2.00
		12	379 (63)	444 (85)	-3.87 (76)*	0	2.50 (11.04)	2.05
	C	10	529 (90)	594 (124)	-2.67 (72)*	5.00 (18.95)	3.75 (13.34)	1.20
		11	512 (73)	596 (124)	-3.54 (56)*	2.50 (11.04)	5.00 (15.19)	0.72
		12	522 (116)	654 (165)	-4.03 (73)*	2.50 (11.04)	3.75 (13.34)	0.21
	D	10	377 (62)	483 (70)	-6.98 (75)*	3.75 (13.34)	0	3.12
		11	386 (56)	457 (64)	-5.20 (76)*	2.50 (11.04)	0	2.05
		12	349 (78)	429 (76)	-4.66 (78)*	0	0	-
	E	10	502 (72)	660 (108)	-7.41 (54.23)*	1.25 (7.91)	8.75 (19.24)	5.00*
		11	535 (87)	676 (133)	-5.40 (63.82)*	3.75 (13.34)	2.50 (11.04)	0.21
		12	452 (81)	573 (133)	-4.74 (72)*	3.75 (13.34)	3.75 (13.34)	-
	F	10	1104 (219)	1314 (326)	-3.22 (72)*	6.25 (16.75)	1.25 (7.91)	2.88
		11	1019 (182)	1359 (294)	-5.79 (69)*	8.75 (22.32)	3.75 (13.34)	1.63
		12	885 (173)	1205 (276)	-6.08 (59.93)*	1.25 (7.91)	3.75 (13.34)	1.05
	G	10	391 (60)	593 (154)	-7.58 (43.11)*	1.25 (7.91)	6.25 (16.75))	2.88
		11	376 (81)	586 (179)	-6.53 (48.32)*	1.25 (7.91)	3.75 (13.34)	1.05
		12	331 (58)	489 (147)	-6.14 (48.32)*	3.75 (13.34)	3.75 (17.50)	2.01
	H	10	470 (106)	577 (109)	-4.25 (72)*	5.00 (15.19)	2.50 (11.04)	0.72
		11	416 (87)	499 (127)	-3.26 (61.88)*	3.75 (13.34)	5.00 (15.19)	0.16
		12	376 (81)	486 (145)	-4.03 (56.95)*	5.00 (15.19)	3.75 (13.34)	0.16
	J	10	465 (92)	677 (135)	-8.10 (75)*	1.25 (7.91)	2.50 (11.04)	0.35
		11	682 (167)	765 (210)	-5.66 (71)*	5.00 (15.19)	3.75 (13.34)	0.16
		12	534 (138)	733 (155)	-7.16 (69.25)*	6.25 (16.75)	0	5.33*
	K	10	682 (167)	765 (210)	-1.74 (62)	12.50 (21.93)	7.50 (18.08)	1.25
		11	534 (138)	733 (155)	-5.61 (67)*	8.75 (19.24)	6.25 (20.22)	2.73
		12	568 (184)	786 (198)	-4.75 (68)*	7.50 (18.08)	5.00 (15.19)	0.46
Incom.	A	10	605 (117)	928 (137)	-11.05 (72)*	2.50 (11.04)	2.50 (11.04)	-
		11	610 (129)	846 (158)	-7.01 (729*	6.25 (20.22)	2.50 (11.04)	1.25
		12	550 (108)	836 (130)	-10.44 (74)*	2.50 (11.04)	2.50 (11.04)	-

	B	10	726 (127)	1061 (179)	-9.35 (73)*	3.75 (17.50)	3.75 (13.34)	2.01
		11	571 (106)	1000 (194)	-11.62 (51.73)*	2.50 (11.04)	6.25 (16.75)	1.41
		12	542 (71)	877 (179)	-10.85 (50.05)*	3.75 (13.34)	2.50 (15.81)	4.05
	C	10	601 (84)	798 (93)	-9.95 (78)*	0	0	-
		11	556 (102)	770 (154)	-7.23 (66.16)*	1.25 (7.91)	1.25 (7.91)	-
		12	469 (74)	659 (114)	-8.74 (65.41)*	1.25 (7.91)	1.25 (7.91)	-
	D	10	528 (63)	692 (171)	-5.44 (43.57)*	0	5.00 (15.19)	4.21*
		11	559 (79)	772 (222)	-5.45 (42.93)*	0	5.00 (15.19)	4.21*
		12	522 (77)	665 (127)	-5.82 (56.94)*	2.50 (11.04)	6.25 (20.22)	1.25
	E	10	818 (218)	1242 (291)	-7.10 (72)*	2.50 (11.04)	6.25 (20.22)	1.25
		11	731 (177)	1089 (238)	-7.02 (66)*	8.75 (19.24)	8.75 (25.03)	3.66
		12	672 (152)	991 (207)	-7.73 (75)*	0	3.75 (13.34)	3.12
	F	10	541 (74)	785 (69)	-14.98 (74)*	2.50 (11.04)	1.25 (7.91)	0.35
		11	509 (56)	749 (106)	-12.60 (59.69)*	2.50 (11.04)	0	2.05
		12	491 (58)	642 (85)	-8.88 (61.41)*	3.75 (17.50)	6.25 (20.22)	1.05
	G	10	429 (78)	635 (185)	-6.37 (49.33)*	0	2.50 (11.04)	2.05
		11	381 (70)	573 (135)	-7.77 (53.39)*	0	3.75 (13.34)	3.12
		12	367 (64)	569 (110)	-9.58 (55.48)*	2.50 (11.04)	5.00 (15.19)	0.72
	H	10	552 (54)	911 (157)	-13.55 (59.24)*	0	1.25 (7.91)	1.01
		11	530 (59)	802 (112)	-13.63 (59.24)*	0	0	-
		12	556 (42)	774 (91)	-13.66 (55.07)*	0	0	-
	J	10	509 (51)	862 (173)	-12.07 (43.25)*	1.25 (7.91)	2.50 (11.04)	0.35
		11	536 (55)	809 (125)	-12.40 (50.56)*	1.25 (7.91)	2.50 (11.04)	0.35
		12	528 (100)	743 (137)	-7.85 (67.62)*	1.25 (7.91)	2.50 (11.04)	0.35
	K	10	517 (174)	746 (176)	-16.01 (51.70)*	2.50 (11.04)	5.00 (15.19)	0.72
		11	504 (116)	734 (250)	-12.11 (48.95)*	10.00 (20.25)	1.25 (7.91)	6.14*
		12	429 (111)	797 (250)	-12.84 (55.47)*	2.50 (11.04)	3.75 (13.34)	0.21
	L	10	553 (124)	851 (164)	-5.78 (76)*	2.50 (11.04)	0	2.05
		11	497 (131)	732 (133)	-5.21 (53.62)*	1.25 (7.91)	1.25 (7.91)	-
		12	502 (124)	713 (115)	-8.41 (52.48)*	1.25 (7.91)	1.25 (7.91)	-
	M	10	553 (124)	851 (164)	-8.44 (66)*	8.75 (22.32)	8.75 (22.32)	-
		11	497 (131)	732 (133)	-7.80 (75)*	1.25 (7.91)	2.50 (11.04)	0.35
		12	502 (124)	713 (115)	-7.50 (70)*	5.00 (15.19)	5.00 (15.19)	-

Note: Mean RTs are in milliseconds. In the sequential condition, max(seq) RTs are given. Test statistics are *T* values) for RTs with degrees of freedom (df) in brackets. Noninteger dfs result due to a correction according to the violation of the equality of variances tested by the Levene's test. Test statistics are $\chi 2$ values for PEs. Test statistics are marked with an asterix if t-tests or $\chi 2$-tests approach a significance level of $p < 0.05$.

8.2. Appendix B: Analyses of the accuracy data for Experiment 3

Single-task errors. The results of the ANOVA are shown in Table B1. Errors did not reduce with training. The manual single tasks (2.6%) were more error prone than the vocal single tasks (1.2%). The S-R and C-R modality-pairing factors as well as their interaction had no effect on the single-task errors. The S-R Non Standard pairing tasks showed a decline in the PEs across sessions while the S-R Standard tasks exhibited an increase (linear contrast).

Table B1. Summary of the ANOVA results on the single-task PEs as a function of task, session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	.05 (1, 20)	.002	.827
Session (quadratic)	.50 (1, 20)	.024	.488
Session *SR	2.28 (4.031, 80.628)	.102	.068
Session *SR (linear)	5.37 (1, 20)	.212	.031
Session *SR (quadratic)	.12 (1, 20)	.006	.736
Session*CR	1.56 (4.031, 80.628)	.072	.192
Session*CR (linear)	2.71 (1, 20)	.119	.116
Session*CR (quadratic)	.001 (1, 20)	<.001	.973
Session*SR*CR	2.28 (4.031, 80.628)	.102	.025
Session*SR*CR (linear)	5.84 (1, 20)	.226	.068
Session*SR*CR (quadratic)	<.001 (1, 20)	.<.001	.990
Task	12.53 (1, 20)	.385	.002
Task*SR	1.52 (1, 20)	.071	.232
Task*CR	2.32 (1, 20)	.104	.143
Task*SR*CR	.19 (1, 20)	.009	.669
Task*Session	.94 (7, 140)	.045	.477
Task*Session (linear)	.29 (1, 20)	.014	.597
Task*Session (quadratic)	<.001 (1, 20)	<.001	.983
Task*Session *SR	1.99 (7, 140)	.091	.060
Task*Session *SR (linear)	3.13 (1, 20)	.135	.092
Task*Session *SR (quadratic)	<.001 (1, 20)	<.001	.975
Task*Session*CR	1.45 (7, 140)	.068	.190
Task*Session*CR (linear)	1.99 (1, 20)	.091	.174
Task*Session*CR (quadratic)	.02 (1, 20)	.001	.898
Task*Session*SR*CR	.47 (7, 140)	.023	.853
Task*Session*SR*CR (linear)	.867 (1, 20)	.042	.363
Task*Session*SR*CR (quadratic)	.003 (1, 20)	<.001	.954
SR	1.26 (1, 20)	.059	.276
CR	.24 (1, 20)	.012	.627
SR*CR	1.40 (1, 20)	.065	.251

Note. In the table above as in following tables if reported the contrasts for the effects are specified in brackets being quadratic or linear.

Mixing Costs in PEs. Mixing costs for the PEs were calculated in analogy to the mixing costs in RTs subtracting the PEs of the single tasks of the pure single-task blocks from the PEs of the single tasks of the mix blocks separately for the manual and the vocal task. The results of the ANOVA on the mixing costs in PEs are summarized in Table B2. Mixing costs in PEs were negative for the two tasks. Hence, there were no costs but benefits for the two tasks, where the manual task (-1.23%) benefited more than the vocal task (-0.21%). This might be due to the fact that only non switch single-task trials of the heterogeneous blocks were taken into account for the mixing task errors. The time course of the mixing-cost distribution differed between the manual and the vocal task. The manual task showed a smaller practice effect on mixing-task errors than the vocal task. The mixing costs in errors decreased across sessions for all tasks whereas they increased for C-R Non Standard tasks.

Table B2. Summary of the ANOVA results on the mixing costs in PEs as a function of task, session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	.22 (1, 20)	.011	.642
Session (quadratic)	.01 (1, 20)	<.001	.946
Session *SR	.80 (7, 140)	.038	.591
Session *SR (linear)	.07 (1, 20)	.003	.802
Session *SR (quadratic)	.18 (1, 20)	.009	.673
Session*CR	1.25 (7, 140)	.059	.280
Session*CR (linear)	5.17 (1, 20)	.205	.034
Session*CR (quadratic)	.13 (1, 20)	.007	.721
Session*SR*CR	.60 (7, 140)	.029	.756
Session*SR*CR (linear)	1.90 (1, 20)	.087	.183
Session*SR*CR (quadratic)	.37 (1, 20)	.018	.548
Task	5.92 (1, 20)	.228	.024
Task*SR	3.11 (1, 20)	.135	.093
Task*CR	1.40 (1, 20)	.066	.250
Task*SR*CR	.03 (1, 20)	.001	.872
Task*Session	2.11 (7, 140)	.096	.046
Task*Session (linear)	4.49 (1, 20)	.183	.047
Task*Session (quadratic)	.41 (1, 20)	.020	.531
Task*Session *SR	.47 (7, 140)	.023	.856
Task*Session *SR (linear)	.64 (1, 20)	.031	.433
Task*Session *SR (quadratic)	.27 (1, 20)	.013	.607
Task*Session*CR	2.15 (7, 140)	.097	.043
Task*Session*CR (linear)	.23 (1, 20)	.012	.634
Task*Session*CR (quadratic)	.11 (1, 20)	.005	.748
Task*Session*SR*CR	.47 (7, 140)	.023	.858
Task*Session*SR*CR (linear)	1.57 (1, 20)	.073	.224
Task*Session*SR*CR (quadratic)	<.01 (1, 20)	<.001	.962
SR	.87 (1, 20)	.042	.362
CR	.06 (1, 20)	.003	.804
SR*CR	2.90 (1, 20)	.126	.105

Manual mixing costs in PEs. Separate ANOVAs with the factors session, S-R pairing and C-R pairing were conducted on the manual and vocal mixing task errors. Table B3 summarizes the statistics on the manual task. There was no significant effect on the manual mixing costs in errors.

Table B3. Summary of the ANOVA results on the manual mixing costs in PEs as a function of session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	1.67 (1, 20)	.077	.212
Session (quadratic)	.18 (1, 20)	.009	.672
Session *SR	.95 (4.625, 92.493)	.045	.450
Session *SR (linear)	.57 (1, 20)	.028	.460
Session *SR (quadratic)	.02 (1, 20)	.001	.892
Session*CR	2.31 (4.625, 92.493)	.104	.055
Session*CR (linear)	3.08 (1, 20)	.133	.095
Session*CR (quadratic)	.20 (1, 20)	.010	.659
Session*SR*CR	.20 (4.625, 92.493)	.010	.953
Session*SR*CR (linear)	.01 (1, 20)	<.001	.929
Session*SR*CR (quadratic)	.10 (1, 20)	.005	.754
SR	2.60 (1, 20)	.115	.123
CR	.71 (1, 20)	.034	.410
SR*CR	1.41 (1, 20)	.066	.250

Vocal mixing costs in PEs. The ANOVA revealed that vocal mixing costs in errors decreased with practice (Table B4). All other effects were not significant.

Table B4. Summary of the ANOVA results on the manual mixing costs in PEs as a function of session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	4.04 (1, 20)	.168	.058
Session (quadratic)	.35 (1, 20)	.017	.563
Session *SR	.28 (3.084, 61.682)	.014	.842
Session *SR (linear)	.23 (1, 20)	.011	.640
Session *SR (quadratic)	.53 (1, 20)	.026	.474
Session*CR	1.07 (3.084, 61.682)	.051	.368
Session*CR (linear)	1.23 (1, 20)	.058	.280
Session*CR (quadratic)	<.01 (1, 20)	<.001	.972
Session*SR*CR	.88 (3.084, 61.682)	.042	.458
Session*SR*CR (linear)	3.67 (1, 20)	.155	.070
Session*SR*CR (quadratic)	.20 (1, 20)	.010	.658
SR	.35 (1, 20)	.017	.562
CR	.55 (1, 20)	.027	.466
SR*CR	2.06 (1, 20)	.093	.167

Dual-task costs in PEs. Dual-task costs in errors were computed in analogy to the dual-task RT costs as the difference of the PEs in the dual-task trials and the non switch single-task trials of the mix blocks of the same task and session. A task x session x S-R pairing x C-R pairing ANOVA was conducted on the dual-task costs on percent errors. All effects of the analysis are summarized in Table B5. The manual task (.68%) yielded less dual-task costs in errors than the vocal task (1.57%).There was a quadratic distribution of dual-task costs in errors over the sessions with the smallest costs for the fifth session. The manual task showed a clear linear practice effect in the costs, whereas the vocal task showed only a drop in error costs for the fourth and the fifth session. The C-R Standard pairing tasks exhibited less dual-task costs than the C-R Non Standard tasks. The S-R pairing effect was opposite for the two C-R pairing groups. Whereas the C-R Standard pairings groups exhibited a decrease in errors when containing S-R Non Standard pairings, the C-R Non Standard groups exhibited an increase in errors when containing S-R Non Standard pairings. The vocal task exhibited a stronger C-R pairing effect than the manual task. The manual task showed stronger costs in errors for the S-R Non Standard than for the S-R Standard pairing tasks. This effect was opposite for the vocal task.

Table B5. Summary of the ANOVA results on the dual-task costs in PEs as a function of task, session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	1.73 (1, 20)	.079	.204
Session (quadratic)	5.86 (1, 20)	.227	.025
Session *SR	.90 (7, 140)	.043	.059
Session *SR (linear)	.53 (1, 20)	.026	.474
Session *SR (quadratic)	.78 (1, 20)	.038	.387
Session*CR	1.38 (7, 140)	.064	.219
Session*CR (linear)	4.01 (1, 20)	.167	.059
Session*CR (quadratic)	1.66 (1, 20)	.076	.213
Session*SR*CR	.70 (7, 140)	.034	.670
Session*SR*CR (linear)	.54 (1, 20)	.026	.470
Session*SR*CR (quadratic)	1.37 (1, 20)	.064	.255
Task	4.90 (1, 20)	.197	.039
Task*SR	11.36 (1, 20)	.362	.003
Task*CR	8.40 (1, 20)	.296	.009
Task*SR*CR	1.50 (1, 20)	.070	.235
Task*Session	1.85 (7, 140)	.085	.082
Task*Session (linear)	6.01 (1, 20)	.231	.024
Task*Session (quadratic)	<.01 (1, 20)	<.001	.995
Task*Session *SR	.78 (7, 140)	.038	.602
Task*Session *SR (linear)	.96 (1, 20)	.046	.339
Task*Session *SR (quadratic)	.07 (1, 20)	.004	.793
Task*Session*CR	2.77 (7, 140)	.122	.010
Task*Session*CR (linear)	2.46 (1, 20)	.109	.133
Task*Session*CR (quadratic)	.09 (1, 20)	.005	.762
Task*Session*SR*CR	1.09 (7, 140)	.051	.376
Task*Session*SR*CR (linear)	5.34 (1, 20)	.211	.033
Task*Session*SR*CR (quadratic)	<.01 (1, 20)	<.001	.992
SR	.10 (1, 20)	.005	.753
CR	3.45 (1, 20)	.147	.078
SR*CR	3.39 (1, 20)	.145	.080

Manual dual-task costs in PEs. The results of the separate ANOVA on the manual dual-task costs in errors are displayed in Table B6. The results show that the manual dual-task cost errors decreased with practice. This practice effect was stronger for the costs in errors of the C-R Non Standard compared to the Standard pairing tasks. S-R Standard pairing tasks yielded less error costs than the S-R Non Standard tasks. There was a significant interaction of the modality pairings. This interaction showed that the C-R Non Standard pairing tasks showed an increase in costs for the S-R Non Standard pairings compared to the Standard S-R pairing tasks. C-R Standard pairing tasks did not vary with S-R pairing factor.

Table B6. Summary of the ANOVA results on the manual dual-task costs in PEs as a function of session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	6.52 (1, 20)	.246	.019
Session (quadratic)	2.38 (1, 20)	.106	.139
Session *SR	1.35 (7, 140)	.063	.230
Session *SR (linear)	1.36 (1, 20)	.064	.257
Session *SR (quadratic)	.56 (1, 20)	.027	.462
Session*CR	2.82 (7, 140)	.124	.009
Session*CR (linear)	6.08 (1, 20)	.233	.023
Session*CR (quadratic)	1.07 (1, 20)	.051	.313
Session*SR*CR	.69 (7, 140)	.033	.678
Session*SR*CR (linear)	.98 (1, 20)	.047	.334
Session*SR*CR (quadratic)	.55 (1, 20)	.027	.467
SR	6.09 (1, 20)	.233	.023
CR	.09 (1, 20)	.004	.767
SR*CR	5.62 (1, 20)	.219	.028

Vocal dual-task costs in PEs. Table B7 displays the results of the ANOVA on the vocal dual-task costs in errors. It revealed significant more error costs for the C-R Non Standard tasks than for C-R Standard tasks. The S-R pairing factor had no influence on the vocal error costs. With practice the S-R Non Standard tasks of the C-R Non Standard groups showed an decrease in costs. The S-R Standard tasks of the C-R Non Standard groups showed an increase in costs. The practice effect did not differ between the S-R modality-pairing groups of the C-R Standard pairing groups. Both decreased.

Table B7. Summary of the ANOVA results on the vocal dual-task costs in PEs as a function of session, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Session (linear)	.50 (1, 20)	.024	.487
Session (quadratic)	3.10 (1, 20)	.134	.094
Session *SR	.40 (3.491, 69.828)	.019	.784
Session *SR (linear)	.02 (1, 20)	.001	.900
Session *SR (quadratic)	.19 (1, 20)	.009	.670
Session*CR	1.37 (3.491, 69.828)	.064	.255
Session*CR (linear)	.19 (1, 20)	.009	.671
Session*CR (quadratic)	.48 (1, 20)	.023	.497
Session*SR*CR	1.06 (3.491, 69.828)	.050	.378
Session*SR*CR (linear)	4.69 (1, 20)	.190	.043
Session*SR*CR (quadratic)	.73 (1, 20)	.035	.402
SR	2.82 (1, 20)	.124	.109
CR	9.21 (1, 20)	.315	.007
SR*CR	.46 (1, 20)	.023	.505

Dual-task costs in PEs for the last session. As for the dual- task RTs it was tested whether dual-task costs in errors of the last session varied with modality pairings. The results for the ANOVA testing S-R and C-R modality-pairing effects on final dual-task costs in PEs are shown in Table B8. The vocal task exhibited more dual-task costs in errors than the manual. For the vocal task errors costs were more frequent for the C-R Non Standard tasks than for the C-R Standard. The dual-task cost in errors for the manual task did not vary across C-R pairings. The S-R pairing effect on costs in errors was reverse. The Standard S-R pairing tasks exhibited more costs in errors than the S-R Non Standard pairing tasks.

For the manual tasks there was a normal S-R pairing effect but a revese C-R pairing effect with Non Standard C-R pairing tasks exhibiting lesser costs in errors than the Standard C-R pairing tasks. Because overall the modality-pairings as their interaction showed no effect on the dual-task costs in errors for the last session the modality-pairing effects on dual-task costs in RTs were not qualified by a speed-accuracy trade-off.

Table B8. Summary of the ANOVA results on the dual-task costs in PEs of session 8 as a function of task, S-R and C-R modality-pairing for Experiment 3.

Effect	*F*(df)	partial η^2	*p*
Task	6.27 (1, 20)	.239	.021
Task *SR	1.79 (1, 20)	.082	.196
Task *CR	7.29 (1, 20)	.267	.014
Task *SR*CR	4.75 (1, 20)	.192	.042
SR	.89 (1, 20)	.043	.357
CR	.02 (1, 20)	.001	.892
SR*CR	1.46 (1, 20)	.068	.241

Dual-task costs in manual PEs for the last session. No modality-pairing effects were observable for the manual dual-task costs in errors for the last session (Table B9).

Dual-task costs in vocal PEs for the last session. The vocal C-R Standard modality-pairing tasks yielded lower dual-task costs in errors than the C-R Non Standard tasks. The other effects did not reach the level of significance. (Table B9)

Table B9. Summary of the separate ANOVA results on the dual-task costs in manual and vocal PEs of session 8 as a function of S-R and C-R modality-pairing for Experiment 3.

Task	Effect	*F*(df)	partial η^2	*p*
Man	SR	1.40 (1, 20)	.065	.251
	CR	1.41 (1, 20)	.066	.249
	SR*CR	3.00 (1, 20)	.130	.099
Voc	SR	.41 (1, 20)	.002	.841
	CR	13.88 (1, 20)	.410	.001
	SR*CR	.75 (1, 20)	.036	.398

8.3. Appendix C: Analyses of the single-task trials of Experiment 4

Single-task RTs. The RTs of the single-task trials that were presented intermixed with the dual-task trials were analyzed in an ANOVA with session (2) as within and S-R pairing (2) and C-R pairing (2) as between subject factor. Only RTs that were associated with a single-task repetition were regarded for the analysis.

Manual single-task RTs. Table C1 displays the summary of the effects for the manual task. The C-R pairing was the only factor reaching significance. The C-R Standard modality-pairing groups had shorter RTs (332 ms) than the C-R Non Standard groups (470 ms). Although missing the conventional level of significance, there was a trend for S-R Standard modality-pairing groups to exhibit longer manual RTs (428 ms) than the S-R Non Standard groups (374 ms). This trend of an inverse S-R pairing effect was already found in Experiment 3.

Table C1. Summary of the ANOVA results on the manual single task RTs as a function of session, S-R and C-R modality-pairing for Experiment 4.

Effect	*F*(df)	partial η^2	*p*
Session	.21 (1, 20)	.011	.649
Session *SR	2.53 (1, 20)	.112	.127
Session *CR	1.63 (1, 20)	.107	.138
Session *SR*CR	2.39 (1, 20)	.010	.649
SR	3.81 (1, 20)	.160	.065
CR	25.84 (1, 20)	.564	<.001
SR*CR	.53 (1, 20)	.026	.477

Vocal single task RTs. For the vocal single-task RTs the same analysis was conducted. As can be seen in the Table C2, no effect reached the level of significance.

Table C2. Summary of the ANOVA results on the vocal single task RTs as a function of session, S-R and C-R modality-pairing for Experiment 4.

Effect	*F*(df)	partial η^2	*p*
Session	.07 (1, 20)	.004	.791
Session *SR	1.98 (1, 20)	.090	.175
Session *CR	1.79 (1, 20)	.082	.196
Session *SR*CR	1.69 (1, 20)	.078	.208
SR	1.41 (1, 20)	.066	.248
CR	1.74 (1, 20)	.080	.202
SR*CR	<.01 (1, 20)	<.001	>.999

Single-task PEs. An ANOVA on the single-tasks PEs as dependent variable with session as within-subject and S-R and C-R pairing as between-subject factors was conducted separately for the manual and the vocal tasks.

Manual single task PEs. Table C3 lists the results for the manual PEs. C-R Standard tasks exhibited lower PEs (1%) than the C-R Non Standard tasks (3%). Missing the conventional level of significance there was a trend that the S-R pairing effect was more pronounced for the C-R Non Standard task errors showing no difference between the S-R pairing tasks for the C-R Standard groups but an increase in PEs for the S-R Standard to the S-R Non Standard tasks of the C-R Non Standard groups.

Table C3. Summary of the ANOVA results on the manual single task PEs as a function of session, S-R and C-R modality-pairing for Experiment 4.

Effect	*F*(df)	partial η^2	*p*
Session	.65 (1, 20)	.032	.429
Session *SR	.24 (1, 20)	.012	.633
Session *CR	.42 (1, 20)	.020	.525
Session *SR*CR	3.76 (1, 20)	.158	.067
SR	1.58 (1, 20)	.073	.223
CR	7.21 (1, 20)	.265	.014
SR*CR	4.00 (1, 20)	.167	.059

Vocal single task PEs. The same analysis was done for the vocal single task PEs. As Table C4 summarizes any factor significantly affected vocal single task PEs.

Table C4. Summary of the ANOVA results on the vocal single task PEs as a function of session, S-R and C-R modality-pairing for Experiment 4.

Effect	*F*(df)	partial η^2	*p*
Session	.85 (1, 20)	.041	.368
Session *SR	.29 (1, 20)	.014	.596
Session *CR	1.26 (1, 20)	.059	.276
Session *SR*CR	3.22 (1, 20)	.139	.088
SR	3.30 (1, 20)	.142	.084
CR	3.53 (1, 20)	.150	.075
SR*CR	.08 (1, 20)	.004	.780