On the mechanisms improving dual-task performance with practice

DISSERTATION

zur Erlangung des akademischen Grades doctor rerum naturalium

(Dr. rer. nat.) im Fach Psychologie

eingereicht an der Mathematisch-Naturwissenschaftlichen Fakultät II
der Humboldt-Universität zu Berlin
von Dipl.-Psych. Tilo Strobach

geboren am 08.09.1978 in Brandenburg/ H.

Präsident der Humboldt-Universität zu Berlin: Prof. Dr. Dr. h. c. Christoph Markschies

Dekan der Mathematisch Naturwissenschaftlichen Fakultät II: Prof. Dr. Peter A. Frensch

Gutachter:

1. Prof. Dr. Torsten Schubert, Ludwig-Maximilians-Universität München
2. Prof. Dr. Peter A. Frensch, Humboldt-Universität zu Berlin
3. Prof. Dr. Harold Pashler, University of California, San Diego

Tag der Verteidigung: 18.12.2009

Abstract

Numerous studies showed that people have difficulty performing two tasks at the same time. This difficulty is indicated by additional performance costs in dual-task situations when compared to single-task situations, i.e. dual-task costs. However, recent evidence has shown a substantial reduction of dual-task costs through practice. The finding of dual-task costs at the beginning and the reduction thereof at the end of practice indicates that this reduction must be accomplished via specific learning mechanisms. Although such mechanisms have been addressed in previous studies, the specific mechanisms contributing to practice related dual-task cost reduction remained unknown. The aim of four studies in the present work is to specify these mechanisms by applying a dual-task situation including a visual and an auditory component task (Schumacher et al., 2001). Investigations on learning mechanisms within the component tasks aimed to identify loci of stage shortening in these tasks through practice. For the first time I showed that component task processing in dual-task situations is mainly shortened through a shortening at the response selection stage. In contrast, investigations on learning mechanisms between the component tasks focussed on the acquisition of task coordination skills. Here I provided evidence that these skills are acquired during dual-task practice and there is no acquisition of these skills during single-task practice. Additionally, I demonstrated that these skills are transferable to alternative dual-task situations. There is, however, no evidence for transfer of these skills to task switching and attentional blink paradigms. In order to further specify the result of the learning mechanisms, I showed that dual-task performance in the visual but not in the auditory task is stable after practice has finished. The present findings on learning mechanisms are integrated into a model of practiced dual-task performance, the latent bottleneck model, and new assumptions in the framework of this model are discussed.

Keywords: dual tasks, practice, learning mechanisms, latent bottleneck model

Zusammenfassung

Zahlreiche Studien belegen, dass Menschen Schwierigkeiten bei der simultanen Ausführung von 2 Aufgaben haben. Diese Schwierigkeiten sind durch zusätzliche Leistungskosten in Doppelaufgabensituationen im Vergleich zu Einzelaufgabensituationen gekennzeichnet (d.h. Doppelaufgabenkosten). Allerdings konnten jüngere Studien eine deutliche Reduktion der Doppelaufgabenkosten am Ende von Übung zeigen. Der Befund von Doppelaufgabenkosten am Beginn und die deutliche Reduktion davon am Ende der Übung indiziert, dass diese Reduktion durch spezifische Lernmechanismen geleistet wird. Obwohl sich frühere Studien bereits mit diesen Mechanismen befassen, bleiben die genauen Mechanismen der Reduktion der Doppelaufgabenkosten durch Übung unbekannt. Das Ziel von vier Studien der vorliegenden Arbeit ist die Spezifizierung dieser Mechanismen durch die Anwendung einer Doppelaufgabensituation mit einer visuellen und einer auditiven Teilaufgabe (Schumacher et al., 2001). Untersuchungen zu Lernmechanismen innerhalb der Teilaufgaben zielten auf die genaue Lokalisation von Verkürzungen der Verarbeitungszeit in diesen Aufgaben während der Übung. Erstmalig konnte ich zeigen, dass die Verkürzung der Aufgabenverarbeitung in Doppelaufgabensituationen vor allem durch eine verkürzte Antwortauswahlstufe erfolgt. Demgegenüber haben Untersuchungen zu Lernmechanismen zwischen den Teilaufgaben auf den Erwerb von Fertigkeiten der Aufgabenkoordination gezielt. Hier habe ich Nachweise erbracht, dass diese Fertigkeiten während der Übung von Doppelaufgaben erwerbbar sind, aber dass kein Erwerb während Einzelaufgabenübung erfolgt. Weiterhin habe ich gezeigt, dass diese Fertigkeiten in alternative Doppelaufgabensituationen transferierbar sind. Allerdings gibt es keinen Nachweis für den Fertigkeitstransfer in Aufgabenwechsel- und Attentional-Blink-Situationen. Um das Ergebnis von Lernmechanismen weiter zu spezifizieren, habe ich gezeigt, dass die Doppelaufgabenleistung in der visuellen aber nicht in der auditiven Teilaufgabe stabil ist nachdem die Übung beendet wurde. Die vorliegenden Befunde zu Lernmechanismen werden in ein Modell von geübter Doppelaufgabenleistung, das Latent Bottleneck Model, integriert und neue Annahmen im Rahmen dieses Modells diskutiert.

Schlagwörter: Doppelaufgaben, Übung, Lernmechanismen, Latent Bottleneck Model

Acknowledgements

First of all, I have to thank the supervisor of the present work, Prof. Dr. Torsten Schubert, for his scientific, financial, cooperative, and personal support.

I wish to thank Prof. Dr. Peter A. Frensch for the possibility to use the facilities in the unit for general psychology at the Department of Psychology of the Humboldt-Universität zu Berlin. I am also grateful to the Deutsche Forschungsgemeinschaft (DFG) for financial support.

Weiterhin möchte ich meinen Kollegen Robert Gaschler, Géza Harsányi, Sabine Schwager, Christine Stelzel und Andre Weinreich für die moralische, persönliche und soziale Unterstützung während meiner Promotionszeit danken.

Tausend Dank auch an meine Mutter Ellen Strobach und meinen Vater Peter Strobach, der diese Zeit leider nicht mehr miterleben kann, für den Grundstein für diesen Weg.

Und natürlich ganz besonders möchte ich mich bei Maika und unserem Sohn Ferenc bedanken, die oft auf mich verzichten mussten. Durch Euch war diese Arbeit nur halb so schwer.

Publications Included

Study 1

Strobach, T., Frensch, P. A., Liepelt, R., & Schubert, T. (under revision). Extensive Dual-Task Practice and the Loci of its Effects in Simultaneous Choice Tasks.

Study 2

Liepelt, R., Strobach, T., Frensch, P. A., & Schubert, T. (submitted). Improved inter-task coordination after extensive dual-task practice.

Study 3

Strobach, T., Frensch, P. A., & Schubert, T. (submitted). Testing the acquisition and transferability of task coordination skills at the end of dual-task practice.

Study 4

Strobach, T., Frensch, P. A., & Schubert, T. (2008). The Temporal Stability of Skilled Dual-Task Performance. In H. D. Zimmer, C. Frings, A. Mecklinger, B. Opitz, M. Pospeschill, & D. Wentura (Eds.), *Cognitive Science 2007. Proceedings of the 8th Annual Conference of the Cognitive Science Society of Germany*. Saarbrücken.

Table of Contents

1. Introduction

Performing two tasks at the same time (i.e., dual tasks) can be extremely difficult but this difficulty is often reduced following a certain amount of practice. For instance, during the first driving lessons learners find it challenging to coordinate the different activities (e.g., changing gear, changing lane, goal maintenance) essential to drive a car (Levy, Pashler, & Boer, 2006). At the end of the lessons most drivers are, however, able to coordinate these activities enabling them to drive safely in road traffic. Or to put it another way, drivers show an improved performance in the dual-task situation of car driving at the end of practice. The present work addresses this practice related improvement of dual-task performance. In particular, I explored the underlying learning mechanisms associated with this improvement as a result of extensive practice. These mechanisms focus on the shortening of processing stages within the component tasks as well as the acquisition of task coordination skills between the component tasks of the dual-task situation. A further aim of the present work to investigate the stability of improved dual-task performance after practice has finished.

1.1 Dual-task processing

When people execute two component tasks simultaneously in dual-task situations, performance in one or in both tasks often deteriorates, indicated by an increase in processing time (RTs) and / or in error rates relative to single-task situations when the tasks are executed separately. This performance deterioration in dual-task situations is referred to as “dual-task costs”. In cognitive psychology, these dual-task costs were observed in various situations, such as simultaneously driving a car and talking on a cell phone (e.g., Strayer, Drews, & Johnston, 2003), arithmetic processing and simultaneous memory retrieval (Oberauer, Demmrich, Mayr, & Kliegl, 2001), manipulations of multiple representations in working memory (Baddeley & Hitch, 1974), and many more.

Dual-task costs are often explained by capacity limitations of the cognitive system. One common assumption of these capacity limitations is a processing bottleneck. This bottleneck allows the processing of only one task to proceed at a time. When the bottleneck is thus occupied by one task, then the other task cannot be executed and is postponed until the first task has left the bottleneck. For the time of the postponement, dual-task costs emerge. Older dual-task studies, however, have not been precise with respect to the ongoing tasks and the underlying processing stages in pinpointing the exact location of the bottleneck responsible for the emergence of dual-task costs (e.g., Vince, 1948).

In order to overcome this constraint, dual-task performance was extensively investigated by means of the Psychological Refractory Period (PRP) paradigm (Logan & Gordon, 2001; Pashler, 1984, 1994; Schubert, 1999; Telford, 1931; Welford, 1952). In common PRP paradigms, two stimuli are presented with varying stimulus onset asynchronies (SOA) and participants are required to respond to both stimuli with distinct motor responses. The typical result in this paradigm is that dual-task costs mainly appear in the second of the 2 presented tasks and increase with shorter SOAs. On the other hand, the performance in the first task is widely unaffected by the SOA manipulation (e.g., Pashler & Johnston, 1989).

As shown in Figure 1A, many authors (e.g., McCann & Johnston, 1992; Pashler, 1994; Pashler & Johnston, 1998; Schubert, 1999) assume a bottleneck at the response selection stage of the component tasks presented in the PRP paradigm (i.e., a central bottleneck model). In addition to a bottleneck at the response selection stage, recent studies assumed bottlenecks at the peripheral perception and / or motor stages causing the emergence of dual-task costs (e.g., De Jong, 1993; Meyer & Kieras, 1997; Sommer, Leuthold, & Schubert, 2001).

1.2 Dual-task processing and practice effects

Despite the numerous findings of considerable performance costs in dual-task situations, a number of recent studies suggested that dual-task processing can be optimized as a result of

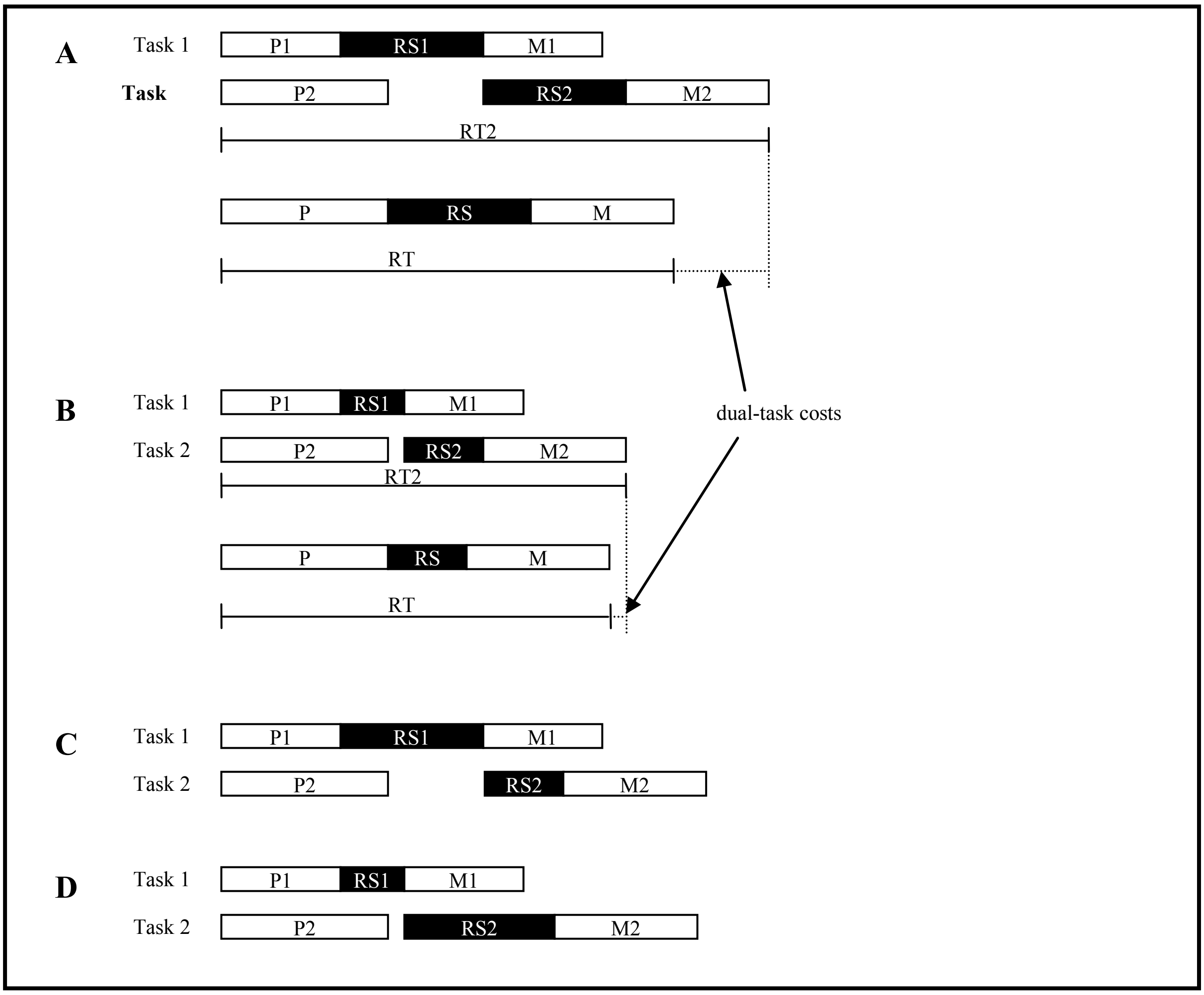

Figure1. Illustration of the hypothetical time relation of processing stages in Task 1 and Task 2 when presented in a dual-task situation with SOA = 0 ms. P1, P2, and P indicate the perception stages; RS1, RS2, and RS indicate the response-selection stages; M1, M2, and M indicate the motor stages. RT2 represents the reaction time in Task 2 in dual tasks; RT stands for the reaction time of Task 2 performed as single tasks. Panel A: Hypothetical time relation in the beginning of practice according to the central bottleneck model. The processing of the response selection stage in Task 2 is postponed until the response selection stage in Task 1 is finished. Due to this postponement, clear dual-task costs mainly emerge in Task 2. Panel B: Hypothetical time relation in the end of practice according to the latent bottleneck model. The dual-task costs in Task 2 are extremely reduced due to the development of a latent bottleneck. Panel C: Hypothetical time relation when the response selection stage of Task 1 is prolonged. The processing of the response selection stage in Task 2 is postponed until the response selection stage in Task 1 is finished. Panel D: Hypothetical time relation when the response selection stage of Task 2 is prolonged. The Task 2-prolongation does not affect Task 1-processing.

extended dual-task practice. This practice related optimization leads to a strong reduction or even a complete elimination of dual-task costs (e.g., Ahissar, Laiwand, & Hochstein, 2001; Hazeltine, Teague, & Ivry, 2002; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Nino & Rickard, 2003; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006; Schumacher et al., 1999, 2001; Spelke, Hirst, & Neisser, 1976; Van Selst, Ruthruff, &

Johnston, 1999). Schumacher et al. (2001), for instance, showed completely eliminated dual-task costs in a dual-task paradigm that consisted of a visual-manual (i.e., the visual task) and an auditory-verbal component task (i.e., the auditory task). In the visual task, participants compatibly responded with finger presses of the right hand to the spatial position of visually presented circles. In the auditory task, participants gave verbal number responses according to the pitch of sine wave tones. While either the visual or the auditory task were presented exclusively in single-task trials, one visual and one auditory stimulus were presented simultaneously (i.e., SOA = 0 ms) in dual-task trials. In the beginning of practice, the data showed significant dual-task RT costs mainly evident in the auditory task. After 5 sessions of practice, Schumacher et al. (2001) reported, however, equal RTs in single-task and dual-task trials in both tasks, indicating a complete elimination of the dual-task costs.

The finding of dual-task costs at the beginning of practice and their strong reduction after extended practice indicates that this reduction must be accomplished via specific learning mechanisms. Although such mechanisms have been addressed in previous studies (e.g., Hirst et al., 1980; Kramer, Larish, & Strayer, 1995; Spelke et al., 1976) the specific learning mechanisms involved in improved dual-task processing are still a matter of debate. This is mainly because the dual tasks applied in these previous studies were not sufficiently sensitive to provide detailed analyses about how proficient dual-task performance is achieved with practice (Hazeltine et al., 2002). Therefore, the main goal of the present work was to investigate the specific learning mechanisms improving dual-task performance with extensive practice.

1.3 Learning mechanisms investigated in the present work

The specific learning mechanisms that might contribute to the reduction of dual-task costs during practice will be outlined next. The present investigations focus on two types of mechanisms. According to the first type of mechanisms, dual-task costs are reduced through a shortening of the processing time of the component tasks that constitute the dual tasks. This shortening might reduce the interference that tasks can exert onto each other (e.g., Ruthruff et al., 2001, 2003). In particular in Study 1 (Chapter 2.1), I asked which processing stages within the component tasks are shortened as a result of dual-task practice?

According to the second type of practice related mechanisms, the dual-task costs are reduced due to the improvement of processes involved in the coordination of the processing streams of two component tasks (e.g., Hirst et al., 1980; Kramer et al., 1995). I assume that this improvement is instantiated by the acquisition or improvement of task coordination skills as a result of practice. The particular aims of Study 2 and 3 (Chapter 2.2) were to focus on the following questions: Does dual-task practice lead to the acquisition of task coordination skills while there is no acquisition during single-task practice? Are these task coordination skills transferable to new task situations?

In order to further characterize the results of the learning mechanisms, I aimed to investigate the development of dual-task performance after the end of practice. In particular, I explored in Study 4 (Chapter 2.3) whether improved dual-task performance remains stable after practice has finished.

After investigating the practice related learning mechanisms, I discuss how these mechanisms precisely contribute to the reduction of the dual-task costs at the end of practice (Chapter 3.1). For that purpose, I introduce the latent bottleneck model (LBM). LBM was proposed by Ruthruff et al. (2003) and Van Selst et al. (1999) and is one possible processing architecture to explain practiced dual-task performance. I will integrate the findings about learning mechanisms into LBM. As a result, I will present a modified model that is consistent with the empirical findings of the present studies. This modified model will explain more precisely how dual-task performance is improved with practice as compared with the model version proposed by Ruthruff et al. and Van Selst et al. In order to test the validity of LBM, I present data consistent with this model of practiced dual tasks (Chapter 2.5).

1.4 The general approach to investigate learning mechanisms

The main rationale of the present studies to investigate specific learning mechanisms was as follows. First, participants accomplished extensive dual-task practice to reduce the performance costs in dual-task situations. In the dual-task situation of the final transfer sessions, I then introduced specific manipulations appropriate to examine specific mechanisms. The analyses of the behavioural data, i.e. RTs and error rates, in the manipulated dual-task situation and at the end of practice allowed me to make conclusions about these mechanisms associated with improved dual-task performance with practice.

In order to precisely investigate the learning mechanisms associated with reduced dual-task costs, the dual-task paradigm of Schumacher et al. (2001) was applied in all of the following studies. This paradigm consists of two simply structured component tasks; a visual task and an auditory task. These tasks allow for well-controllable manipulations of component-task processes and exact analyses of the effects of these manipulations on the dual-task performance. Moreover, the dual-task situation of Schumacher et al. allows for an extreme reduction or even a complete elimination of dual-task costs after a moderate amount of practice sessions (see also Hazeltine et al., 2002; Tombu & Jolicoeur, 2004).

2. Summary of the studies

2.1 Study 1: Shortening of component task processing stages with practice

2.1.1 Introduction

The reduction of dual-task costs as a result of practice was associated with learning mechanisms that are located within the component tasks of the dual-task situation. In particular, a number of previous studies assumed that the shortening of the processing stages in the component task leads to the optimization of dual-task processing with practice (e.g., Anderson, Taatgen, & Byrne, 2005; Dux et al., 2009; Maquestiaux, Laguẽ-Beauvais, Ruthruff, & Bherer, 2008; Ruthruff et al., 2001, 2003, 2006; Sangals, Wilmer, & Sommer, 2007; Van Selst et al., 1999). Sangals et al. (2007), for example, applied the lateralized readiness potential (LRP) to assess practice effects in the component tasks of a PRP situation. These findings showed that dual-task practice affects mainly the duration of processes before the start of the motor stage (i.e., pre-motor stages) while processes at the motor stage were widely unaffected by practice. These findings were consistent with results of regression analyses in studies of Ruthruff et al. (2001) and Van Selst et al. (1999).

However, the LRP findings of pre-motor stage shortening in the Sangals et al. (2007)-study do not allow more specific conclusions about the loci of practice related stage shortening in the component tasks to be made. This is because pre-motor stages include at least two distinguishable processing stages (e.g., Sternberg, 1969; Pashler & Baylis, 1991): the perception stage and the response selection stage. That is, it remains unclear whether processes located at the perception stage, at the response selection stage, or a combination of both stages, are shortened with dual-task practice. Here I will present a more precise investigation of stage shortening.

2.1.2 Research aim and general methods

The aim of Study 1 was to investigate the specific loci of stage shortening in component task processing after extensive dual-task practice. The specific loci of shortening were separately assessed for processes at the perception stage, the response selection stage, and the motor stage. Experiments 1 and 2 assessed stage shortening in the auditory task and in the visual task of the dual-task situation of Schumacher et al. (2001), respectively. Importantly, the present analyses mainly focussed on stage shortening in dual-task situations.

The general methods in Study 1 were as follows. First, participants conducted 8 sessions of practice similar to the design of Schumacher et al. (2001). To assess stage shortening in the component tasks during practice, I applied a transfer logic originally proposed by Pashler and Baylis (1991) in following transfer sessions. In order to identify the particular processing stages which potentially undergo a practice related shortening, I introduced transfer manipulations separately targeting processing routines at the perception, the response selection, or the motor stages. As a consequence, the processing routine may or may not be applied in the transfer situation. The transfer manipulation will lead to an increase in processing time if participants cannot use a processing routine any longer that was speeded-up due to learning. On the other hand, no increase in processing time is expected if learning has not led to a shortening of a processing routine.

2.1.3 Stage shortening in the auditory task (Experiment 1):

In Experiment 1, I focussed on stage shortening in the auditory task. Possible shortenings of the processing time at the response selection stage of that task were assessed by comparing the performance of participants before and after a manipulation of the rules mapping the auditory stimuli to the vocal motor responses. While participants practiced a compatible mapping between tone pitches and verbal numbers, they performed an incompatible mapping during the transfer session. Changing the mapping rules during transfer resulted in a tremendous prolongation of the overall RTs compared to those at the end of practice, before mapping was manipulated. This result suggests a practice related shortening of stimulus-response mapping located at the response selection stage.

In order to assess a shortening at the perception stage due to improved stimulus identification, new un-practiced auditory stimuli were introduced in the transfer session. That is, when sine wave tones were presented during practice, participants were transferred to a situation including the presentation of square wave tones. This manipulation led to a small prolongation of the overall RTs in the transfer compared to the last practice session reflecting some shortenings of the stimulus identification located at the perception stage.

In order to assess possible shortenings at the motor stage in the auditory task, the number words were changed in the transfer session. The introduction of new verbal responses during transfer revealed no increase of the RTs compared to the final learning session; this suggests that changes in the time needed to execute the verbal motor responses are not a factor that contributes to the practice related changes in the overall RT of the auditory task.

2.1.4 Stage shortening in the visual task (Experiment 2):

In the following experiment, I focussed at stage shortening in the visual task. Possible shortenings in the time needed to map the stimulus information onto the motor response information at the response selection stage were investigated by comparing the performance before and after changing the mappings. While participants practiced a position mapping between visual stimuli and manual responses, they performed a size mapping in a final transfer session. Similar to the auditory task, the present findings showed strongly prolonged RTs in the visual task after changing the stimulus-response mapping compared to the RTs before the manipulation was introduced. These prolonged RTs indicated practice related reductions of processes located at the response selection stage of the visual task.

To detect a possible practice related shortening of processes involved in the identification of the circles at the perception stage, new visual stimuli were introduced after the presentation of old visual stimuli. That is, when circles were presented during practice, triangles were presented during transfer. The lacking effect of the introduction of new stimuli on the RTs is consistent with the hypothesis that a possible shortening of the routines in identifying the visual stimuli did not contribute to the overall practice related shortening in the visual task.

In order to assess learning at the motor stage of the visual task, the manual responses were changed at the end of practice. After participants practiced with the finger of one hand they were instructed to respond with the fingers of the other hand during transfer. The transfer manipulation did not affect the performance in the dual-task trials, which is consistent with the hypothesis that RT shortenings in the visual tasks did not contribute to a possible shortening of processes of manual response execution.

2.1.5 Discussion

The present Study 1 provides comprehensive and detailed conclusions about stage shortening in component tasks during dual-task practice. Taken together, the results of Experiment 1 and 2 indicate shortenings at the response selection stages in both component tasks at the end of dual-task practice. Additionally, there are indications for a shortening of processes involved in the initial perception of the stimuli in the auditory task, while I found no evidence for shortened processing at the perception stage in the visual task. Assessing processes of response execution, the data support the assumption that the motor stages of both component tasks remained unaffected by practice in dual-task situations.

The adaptation of the transfer logic of Pashler and Baylis (1991) to the dual-task paradigm of Schumacher et al. (2001) allowed me to separately assess the shortening of component-task processing at different stages at the end of dual-task practice for the first time. This separate assessment shows the loci of stage shortening more precisely than any previous studies on practice effects in the component tasks (Ruthruff et al., 2001; Sangals et al., 2007; Van Selst et al., 1999); these studies allowed no differentiation between perception stage and response selection stage shortening. Furthermore, I assume that the different outcomes in Experiments 1 and 2 (i.e., perception stage shortening in the auditory task vs. no perception stage shortening in the visual task) indicate that stage shortening is attributed to the specific tasks and the specific processes involved in task processing. That also means the manipulation of different processes in the component tasks could potentially result in alternative conclusions about stage shortening. The specific contribution of these learning mechanisms within the component tasks to the reduction of dual-task costs with practice will be discussed in Chapter 3.1.1.

2.2 Study 2 and 3: task coordination skills acquired with practice

2.2.1 Introduction

In addition to learning mechanisms improving dual-task performance within the component tasks (i.e., stage shortening), the reduction of dual-task costs was further associated with mechanisms between the component tasks in a dual-task situation. Assumptions about this type of mechanisms basically extends the central bottleneck model (e.g., Pashler, 1994) by introducing assumptions about active control processes into the cognitive architecture of dual-task processing in the beginning of practice (De Jong, 1995; Logan & Gordon, 2001; Luria & Meiran, 2003, 2005, 2006; Meyer & Kieras, 1997; Schubert & Szameitat, 2003; Sigman & Dehaene, 2006; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006; Umilta, Nicoletti, Simion, & Tagliabue, 1992). These processes were associated with the coordination of processing streams of two tasks in dual-task situations. However, I assume that, as a result of extended practice, participants acquired task coordination skills that enable an efficient coordination of the processing streams of two component tasks at the end of training (Kramer et al., 1995; Maquestiaux, Hartley, & Bertsch, 2004; Meyer & Kieras, 1997).

The acquisition of task coordination skills representing one type of learning mechanisms of improved dual-task processing was investigated in the following sections. I investigated the acquisition of task coordination skills by testing hypotheses about two properties of these skills: the *dual-task practice hypothesis* and the *transfer hypothesis* (see also Hirst et al, 1980; Kramer et al., 1995).

2.2.2 Investigating the acquisition of task coordination skills: the dual-task practice hypothesis

2.2.2.1 Introduction

According to the dual-task practice hypothesis, task coordination skills are acquired under conditions of dual-task practice when two component tasks are presented simultaneously. In contrast, no task coordination skills are acquired under conditions of single-task practice when component tasks are presented separately. Although these ideas about task coordination skills were previously addressed by several studies (Damos & Wickens, 1980; Kramer et al., 1995; Ruthruff et al., 2006), there is to my knowledge no empirical evidence that allows the unequivocal inference of the existence of such type of skill acquisition during dual-tasks practice compared to single-task practice.

Ruthruff et al. (2006), for example, investigated the effects of single-task practice and of dual-task practice of a PRP-like paradigm on the dual-task performance at the end of practice. The authors assessed the dual-task performance in several groups of participants that practiced component tasks under different conditions. One of the groups practiced an auditory-verbal and a visual-manual choice reaction task in dual-task situations for 8 sessions (group 1). A further group exclusively practiced the auditory-verbal task in single-task situations for the same amount of sessions (group 2). In following test sessions, both groups performed the auditory-verbal and the visual-manual task in dual-task situations. The results showed similar improvement of the dual-task performance in the dual-task learning group 1 and in group 2 that practiced only the auditory-verbal task in the test sessions. This finding suggests that dual-task practice does not lead to the acquisition of task coordination skills. Consequently, improved dual-task performance is exclusively the result of the improved processing of component tasks (see also Ruthruff et al., 2001, 2003; Van Selst et al., 1999).

However, several authors assumed that no task coordination skills are acquired in PRP paradigms as applied by Ruthruff et al. (2006) when the same task, in this case the first task, is continuously prioritized (Bherer et al., 2005, 2008; Glass et al., 2000). The execution of the second task, however, should always succeed the execution of the first task. This fixed order of response execution in PRP paradigms does not seem ideal for the practice related development of task coordination skills, as participants are not instructed for concurrent task performance. In contrast to first-task prioritization as in the PRP-paradigm, task coordination skills may only emerge when participants are explicitly trained to perform two tasks concurrently (Bherer et al., 2005, 2008). I assume that this is the case when participants are instructed for equal priority on two tasks in dual-task situations during practice. Therefore, I investigated the acquisition of task coordination skills after dual-task practice with equal-priority instructions in the present work.

2.2.2.2 Research aim and general methods

The Experiments 1 in Study 2 and in Study 3 aimed to provide empirical evidence for the acquisition of task coordination skills as a result of dual-task practice compared to the effects of single-task practice. In order to look for this evidence, I compared the dual-task costs between two groups of participants in a final transfer session after they had performed 8 learning sessions. One of the groups, the dual-task group, trained the visual task and the auditory task under dual-task and single-task conditions similar to the design of Schumacher et al. (2001). In this design, participants are instructed for equal priority on both tasks. The other group, the single-task group, practiced both tasks exclusively under single-task conditions. If a simple improvement of the component tasks, as suggested by the data of Ruthruff et al. (2006), may explain the practice related reduction of dual-task costs, then the training of component tasks in the dual-task and single-task groups should lead to a reduction of the dual-task costs of a similar amount. However, if participants acquire task coordination skills, training in the dual-task group should lead to an advantage in the dual-task performance compared with the performance in the single-task group at the end of practice.

2.2.2.3 Results

The results of the final transfer session showed improved dual-task performance in the dual-task group compared to the dual-task performance of the single-task group. In particular, dual-task RT costs were reduced in the auditory task after dual-task practice. I found this advantage in the dual-task group in Experiment 1 of Study 2 and this finding was replicated with different groups of dual-task and single-task learners in Experiment 1 of Study 3.

2.2.2.4 Discussion

The data of the present work support the dual-task practice hypothesis suggesting the acquisition of task coordination skills during dual-task practice and not during single-task practice. Importantly, no previous study on dual-task learning (e.g., Ruthruff et al., 2006) has conducted a controlled comparison of dual-task and single-task learning on task coordination skills. The present findings, however, demonstrate for the first time that practice of two tasks under dual-task conditions is more effective in reducing dual-task costs than practicing two tasks separately. They are consistent with the assumption that dual-task practice results in the acquisition of skills in addition to skills acquired during single-task practice.

The present data showed that improved dual-task performance is more than practice effects within the component tasks as suggested by studies of Ruthruff and colleagues (Ruthruff et al., 2001, 2003, 2006; Van Selst, 1999). The data indicated that one important learning mechanism for a practice related reduction of dual-task costs is associated with the acquisition of task coordination skills. The specific contribution of these learning mechanisms to the reduction of dual-task costs with practice will be discussed in Chapter 3.1.2.

2.2.3 Investigating the transferability of task coordination skills: the transfer hypothesis

2.2.3.1 Introduction

The transfer hypothesis assumes that task coordination skills are not specific to the task situation presented during practice. According to Kramer et al. (1995), these skills should be independent from the practiced tasks and should to some extent, be transferable to new task situations. The transfer to new task situations is essential to show that task coordination skills are improved through practice, and that learning entails more than learning the specific component tasks of the practiced dual-task situation (Bherer et al., 2008).

Based on Klauer (2001), in the following sections, I have distinguished the range of transfer into two types of transfer effects: Near transfer effects and far transfer effects. Near transfer effects can be investigated between tasks of the same class that are structurally similar and have many common elements, e.g. different dual-task situations. In contrast, far transfer effects are investigated between tasks of different classes that are structurally dissimilar and have fewer common elements, e.g. dual-task situations and situations of other executive tasks such as task switching (Karbach & Kray, in press).

So far, no study directly tested the near and far transferability of task coordination skills acquired during dual-task practice compared to single-task practice. However, two lines of research exist that are promising for the assumption of transferable task coordination skills. In the first line of research, Kramer et al. (1995; Bherer et al., 2005, 2008; Kramer, Larish, Weber, & Bardell, 1999) investigated the transfer of task coordination skills after dual-task practice with variable priority instructions on two tasks and after dual-task practice with fixed priority instructions on two tasks. The transfer was tested in structurally similar task situations (i.e., near transfer tests); in particular, in new dual tasks. The findings in these transfer situations revealed improved dual-task performance after practice with variable priority instructions. Based on these findings, the authors assumed that this type of practice allows for the acquisition of task coordination skills that may be transferable to alternative situations.

However, this assumption of transferable task coordination skills is not conclusive regarding the purpose of the present study, i.e. the investigation of the transfer hypothesis. This is because the studies of Kramer and colleagues (Bherer et al., 2005, 2008; Kramer et al., 1995, 1999) included no control condition in which participants accomplished single-task practice exclusively before they were tested in new dual-task situations. Consequently, these studies do not allow for a comparison of the effects of dual-task practice with the effects of single-task practice; however, such a test would be essential to investigate the transfer hypothesis of task coordination skills. Therefore, I will investigate the performance in a new dual-task situation after one group of learners practiced dual tasks and one group of learners practiced single tasks here.

In a further line of research, a number of studies showed that practice of action video games is effective to improve basic attentional skills (Basak, Boot, Voss, & Kramer, 2008; Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Castel, Pratt, & Drummond, 2005; Green & Bavelier, 2003, 2006a, 2006b, 2007). These basic attentional skills enable an improved performance in situations when two tasks are presented simultaneously or almost simultaneously (Boot et al., 2008; Green & Bavelier, 2003). Importantly, these skills were tested in experimental paradigms structurally dissimilar to the game situation presented during practice (i.e., far transfer tests). These paradigms were task switching (Roger & Monsell, 1995) and attentional blink (Raymond, Shapiro, & Arnell, 1992). However, it remains an open question whether task coordination skills acquired during dual-task practice are transferable to these structurally dissimilar tasks. Therefore, I will investigate far transfer effects after dual-task and single-task practice to paradigms such as task switching and attentional blink here.

2.2.3.2 Research aim and general methods

The aim of Experiments 2 and 3 in Study 2 as well as of Experiment 2 in Study 3 was to provide evidence for the transfer hypothesis; namely that task coordination skills acquired during dual-task practice are transferable to new task situations. The transfer hypothesis is tested in several near and far transfer tests. For the sake of brevity, I will describe the specific transfer tests in the subsequent chapter.

Basically, the near and far transfer tests were conducted at the end of dual-task practice and at the end of single-task practice. Dual-task practice was identical to the dual-task practice of Schumacher et al. (2001), including the visual task and the auditory task, while single-task practice included the separate training of both component tasks. To investigate if task coordination skills are transferable, tasks were changed between the learning situations and the transfer situations after dual-task and single-task practice. The comparison of the performance in the changed task situations after dual-task practice and after single-task practice allows inference about the transferability of task coordination skills. According to the transfer hypothesis, these changes should not lead to the disappearance of the performance advantage after dual-task practice compared with the performance after single-task practice. However, if these skills are not independent from the tasks presented during practice and are not transferable to new task situations then the dual-task practice advantage should disappear when these changes are introduced during the transfer tests.

2.2.3.3 Rationale, Methods, and Results of near transfer tests of task coordination skills[1]

In order to test for near transfer, I introduced new dual-task situations after dual-task practice and after single-task practice. In the first dual-task transfer experiment the independence of the task coordination skills from the specific visual task presented during practice of the Schumacher et al. (2001) paradigm was tested (Experiment 2, Study 2). For this purpose,

[1] Note that some of the data of Chapter 2.2.3.3 were previously published in Liepelt (2006).

dual-task and single-task learners performed a final transfer session in which the stimulus-response mapping in the visual task was changed from a position mapping to a size mapping after practice. The data in the transfer situation showed improved dual-task performance in the dual-task group compared to the performance in the single-task group. This improved dual-task performance was indicated by reduced dual-task RT costs in the auditory task. This result indicated that the acquired task coordination skills are independent from the specific visual task presented during practice and are transferable to a new visual dual-task situation.

In a second transfer experiment, I tested whether the acquired task coordination skills are independent from the specific auditory task presented during training (Experiment 3, Study 2). In order to assess this independence, the auditory task was manipulated in a final transfer session by changing from a compatible mapping to an incompatible mapping between tone pitches and numbers after practice. Similar to the previous experiment, the second dual-task transfer situation revealed reduced dual-task RT costs in the auditory task in the dual-task group compared to the costs in the single-task group. This result indicated that the acquired task coordination skills are independent from the specific auditory task presented during practice and are transferable to a new auditory dual-task situation.

In a third transfer experiment, I tested whether the acquired skills are independent from both the specific visual task as well as the specific auditory task presented during practice (Experiment 2, Study 3). Therefore, the stimulus-response mapping rules in both component tasks were changed. When both component tasks, the visual task and the auditory task, were changed, the RT data showed similar dual-task costs after single-task and dual-task practice. However, the data showed reduced error costs in the auditory task after dual-task practice compared to the error costs after single-task practice. These data provide hints for the acquisition of task coordination skills that are independent from both component tasks presented in dual tasks. That means they are transferable to a dual-task situation with two changed component tasks. The data of the three near transfer tests basically support the assumption of the transfer hypothesis of task coordination skills. They are extensively discussed in a subsequent chapter (Chapter 2.2.3.5).

2.2.3.4 Rationale, Methods, and Results of far transfer tests of task coordination skills

In order to test for transfer effects of task coordination skills to tasks that are structurally dissimilar from dual tasks (i.e., far transfer), the performance of the dual-task and the single-task groups were investigated in transfer situations of a task switching and an attentional blink paradigm (Experiment 2, Study 3). In order to confirm an equal performance level in these tasks before practice, the dual-task group and the single-task group conducted pre-tests including both transfer tasks. After practice was finished, both groups performed a post-test allowing investigation whether task coordination skills are transferable to situations of task switching and attentional blink paradigms.

In the first experimental situation testing for far transfer, I tested if task coordination skills acquired during dual-task practice of the Schumacher et al. (2001) type are transferable to a task switching paradigm. This paradigm was similar to the situation introduced by Rogers and Monsell (1995, Experiment 1) in which participants conducted a letter identification task and digit identification task. Both tasks were presented in blocks including switches between the two tasks and repetition of one task. The RTs of the task switches and task repetitions were similar in the dual-task group and the single-task group during pre-test and post-test. That is, these data showed no evidence for a successful far transfer of task coordination skills from dual-task practice to an experimental situation of the task switching paradigm.

In the second experimental situation testing for far transfer, the performance in an attentional blink paradigm was investigated in the dual-task group and in the single-task group before (i.e., pre-test) and after practice (i.e., post-test). The selected attentional blink paradigm was similar to the situation introduced by Raymond et al. (1992, Experiment 2). In this situation participants were instructed to report a white letter and the presence of a capital

X in a stream of rapidly presented distracter letters. The analysis of the attentional blink paradigm showed similar rates of correct reports in the dual-task group and in the single-task group during pre-test and during post-test. These findings provide no evidence for far transfer of task coordination skills acquired during dual-task practice to the present experimental situation of an attentional blink paradigm.

2.2.3.5 Discussion

Summarizing the results of the near and far transfer tests, task coordination skills are transferable to a dual-task situation with a changed visual task and to a dual-task situation with a changed auditory task. There are also indications that these skills are transferable to a dual-task situation including changes in both the visual and the auditory task. Focussing on the present task switching and attentional blink paradigms, I found no evidence for far transfer effects of task coordination skills.

The findings of dual-task practice advantage in the near transfer tests with changes in either the visual task or the auditory task, as well as with changes in both component tasks provided evidence that task coordination skills acquired during dual-task practice are transferable to new dual-task situations. They thus provided evidence for a hypothesis about an important property of task coordination skills: the transfer hypothesis. No other study on dual-task learning (e.g., Bherer et al., 2005, 2008; Kramer et al., 1995) has shown the transferability of task coordination skills after dual-task practice in comparison with single-task practice. Furthermore, the findings of the present experiments may be in contrast to Kramer et al. who assumed that transferable task coordination skills are acquired exclusively under conditions of dual-task practice with variable compared with fixed priority instructions. The present experiments, however, demonstrated that these task coordination skills are also transferable after dual-task practice with fixed priority on two tasks when compared to the performance in the transfer situations after single-task practice.

In tasks dissimilar to the practice situation (i.e., task switching and attentional blink) I found no far transfer effects of task coordination skills. These findings indicate that the transferability of task coordination skills is limited to tests of near transfer. In contrast to findings of action video game practice (e.g., Boot et al., 2008; Green & Bavelier, 2003), conducting the dual-task practice was, therefore, not efficient to enable the acquisition of task coordination skills that are transferable to a task switching and an attentional blink paradigm.

2.3 Study 4: The stability of improved dual-task performance after practice

2.3.1 Introduction

A further question of the present work is to investigate dual-task performance after practice had finished. This investigation should show how dual-task performance develops over time after the end of dual-task practice. In particular, the development of dual-task performance after practice allows making conclusions about the stability of dual-task improvement, a result of the practice related learning mechanisms outlined in the previous chapters.

So far, there are only a few studies providing empirical data that may be related to the issue of the stability of improved dual-task performance over time. For example, Bherer et al. (2005) analyzed the performance in single-task and dual-task situations 4 to 6 weeks after the end of 5 practice sessions. The performance difference between single tasks and dual tasks did not differ before and after the pause in a compound measure across the presented component tasks. Consequently, the authors assumed that dual-task performance was stable after practice had finished (Bherer, personal communication, April 16, 2007).

Although this finding suggests stable dual-task performance over time, it needs to be treated with caution because only a few participants appeared for the follow-up session compared to the learning sessions. Moreover, the compound measure across both component tasks used by Bherer et al. (2005) did not enable specific conclusions about the stability of the individual tasks. In the present work, I therefore conducted a well-controlled test of dual-task performance stability with separate analyses of the individual component tasks.

2.3.2 Research aim and general methods

The aim of Study 4 was to investigate the stability of improved dual-task performance after practice had finished. As in the previous studies of the present work, the stability was investigated in the dual-task design of Schumacher et al. (2001). Participants practiced the dual-task situation for 10 sessions and performed a retention session after a pause of six weeks without practice. Importantly, participants performed the identical visual task and auditory task in dual-task conditions in the sessions immediately before and after the pause. A comparison of the dual-task performance in both tasks before and after the pause reveals the degree of stability of improved dual-task performance over time. If improved dual-task performance is stable after practice, one would predict similar dual-task performance in the sessions before and after the pause. Conversely, if dual-task performance impairs after the pause, this would be in contrast with the assumption that improved dual-task performance is stable.

2.3.3 Results and Discussion

The analyses of the dual-task performance showed that which effects the administration of a long pause of dual-task practice has, depends on the specific component task to be performed. For the visual task, the analysis of the data in the dual-task conditions before and after the pause revealed a similar performance when considering RTs and, interestingly, it revealed reduced error costs after a pause of six weeks. The analysis of the auditory task revealed, however, an impaired RT and error performance in the dual-task conditions after a long pause of six weeks. This suggests that dual-task performance of this task is not stable across time.

The present experiment is the first systematic analysis that allows for conclusions about the stability of dual-task performance after practice (e.g., Bherer et al., 2005). This is because the present test for dual-task performance stability allows for separate analyses of the two component tasks. These separate analyses extend the preliminary findings of Bherer et al.

The reason for the different degrees of stability of the visual task and the auditory task may be the different degrees of processing automatization in the two tasks (see also Ruthruff et al., 2006). According to Shiffrin and Schneider (1977), highly automatic task processing is stable while less automatic task processing is not stable over time. In the present dual-task situation, the visual task includes a spatial compatible mapping between stimulus locations and manual responses. This compatible mapping might allow for a high level of automatization and, therefore, stability in the visual dual-task processing after practice. In contrast, the mapping between tone pitches and numbers in the auditory task is rather arbitrary leading to a lower level of processing automatization in this task after practice. This lower level of automatization does not allow the auditory task to maintain the level of dual-task processing after practice had finished.

However, the present experimental design did not allow for assured conclusions about which specific learning mechanisms are attributed to the development of the dual-task performance in the visual task and the auditory task over time. That is, it remains unknown whether and how mechanisms within the component task (i.e., stage shortening) or between the component tasks (i.e., task coordination skills) are affected by the time delay. This investigation is a promising question for future studies.

2.4 Summary of the empirical findings

Study 1 showed that mainly the mapping between stimuli and responses at the response selection stages in the visual task and the auditory task in dual tasks is shortened during dual-task practice of the Schumacher et al. (2001) paradigm. In addition, hints of stage shortening at the perception stage in the auditory task indicate that response selection stage shortening is not the exclusive locus of shortened component-task processing. However, the analyses of the perception stage in the visual task and the motor stages in both tasks demonstrated no evidence for additional loci of stage shortening in these tasks.

Study 2 and 3 showed that task coordination skills are acquired during dual-task practice compared with single-task practice. These skills are transferable to dual-task situations with changes in either the visual task or the auditory task as well as to a dual-task situation with changes in both component tasks, i.e. near transfer effects. These findings support the dual-task practice hypothesis and the transfer hypothesis about task coordination skills. However, the present studies provided no evidence for far transfer effects of task coordination skills to task switching and attentional blink paradigms showing the limits of transferability of these skills.

Study 4 of this work showed that the stability of practiced dual-task performance is task-dependent. While the performance in the visual task was stable, the performance in the auditory task was impaired 6 weeks after the end of practice.

2.5 The processing architecture of practiced dual tasks: LBM

2.5.1 Introduction

As outlined above, the important aspect of the present work is the precise investigation of learning mechanisms improving dual-task performance as a result of practice. However, this investigation presented so far leaves the question open of how these mechanisms exactly contribute to the reduction of dual-task costs. I assume that knowledge about the underlying cognitive processing architecture allows for a better understanding of the contribution of the learning mechanisms to dual-task cost reduction after practice.

Presented in Figure 1B, one recently proposed model to explain practiced dual-task processing is LBM (Anderson et al., 2005; Lien, Ruthruff & Johnston, 2006; Pashler, 1998;

Ruthruff et al., 2003; Schubert 2008). According to this model, extensive practice may cause that bottleneck processes are still at work even if they do not lead to the emergence of dual-task costs. In particular, it has been proposed that extensive practice may lead to an extreme and unequal shortening of the response selection stages (i.e., the bottleneck processes) in the two component tasks. In that case, a so-called latent bottleneck may emerge that represents a particular type of architecture of dual-task processing in which bottleneck stages are still involved but are scheduled in a way that avoids any temporal overlap between them. Note that the assumption of still existing bottleneck processes in LBM is in contrast to models assuming reduced dual-task costs are evidence for parallel processing such as EPIC (Meyer & Kieras, 1997). Nevertheless, the question how dual tasks are processed after practice with the present dual-task situation (Schumacher et al., 2001) remains open.

2.5.2 Research aim and general methods

The aim of the next section is to investigate the processing architecture of practiced dual tasks. In order to achieve this, I tested several theoretical predictions of LBM by reanalyzing data of the learning experiments.

The theoretical predictions of LBM can be tested by separate manipulations of the duration of bottleneck processes at the response selection stages of the two component tasks after practice related reductions of the dual-task costs, and by assessing the related effects on the RTs of the concurrent tasks (see also Hazeltine et al., 2002; Van Selst et al., 1999). As shown in Figure 1C, LBM predicts that prolonging the duration of the bottleneck processes in the shorter of the two tasks (Task 1), these processes might come into conflict with the bottleneck processes of the longer task (Task 2) leading to the following predictions: First, the RTs in Task 1 should increase for a certain amount of time. Second, the prolongation of the RTs in Task 1 should be completely propagated into the processing time of Task 2 via the bottleneck mechanism between both tasks. This should cause an equal amount of RT increase in both tasks.

As shown in Figure 1D, when prolonging the duration of the bottleneck processes in Task 2, these processes will not come into conflict with the bottleneck processes of Task 1. In particular, RTs in Task 2 should increase in duration after the manipulation. However, this increase should lead to a selective effect only on the RTs in that task because there is no possibility of a carry over of Task 2 effects onto Task 1 RTs.

Previous studies using a similar dual-task design as in the present studies demonstrated that the visual task is the shorter and the auditory task is the longer task in dual-task trials (Hazeltine et al., 2002; Schumacher et al., 2001; Tombu & Jolicoeur, 2004). Therefore, the manipulation of the mapping rules at the response selection stage in the visual task at the end of practice allows for the investigation of the effects of Task 1 manipulation on Task 1 and Task 2 RTs. This type of manipulation was conducted in Experiment 2 of Study 1. On the other hand, the manipulation of the mapping rules in the auditory task allows for the investigation of the effects of Task 2 manipulation on both tasks. This type of manipulation was conducted in Experiment 1 of Study 1. In order to precisely analyse the manipulation effects in dual-task situations, only those trials were selected from the data set in which the response execution in the visual task preceded the response execution in the auditory task.

A similar test of latent bottleneck processing was demonstrated previously in Liepelt (2006) after 8 practice sessions with the Schumacher et al. (2001) paradigm. In short, the findings in this previous test were consistent with the predictions of LBM. These findings thus showed that bottleneck stages are still existent after practice. Nevertheless, while participants had already performed dual-task practice for a long time in that study, it might be the case that bottleneck processes are not eliminated until they accomplish more extensive practice, which would be inconsistent with LBM. Therefore, the predictions of LBM were tested after 12 sessions of dual-task practice in the present work.

2.5.3 Results and Discussion

The manipulation of the response selection stage in the visual task resulted in a similar RT prolongation in both tasks. That is, the prolongation of *145 ms* in the visual task after the end of practice was propagated completely into the auditory task leading to a similar prolongation of *153 ms* in that task, $F(1, 8) < 1$. On the other hand, the manipulation of the response selection stage in the auditory task resulted in a RT prolongation of *238 ms* in that task while the RTs increased by only *19 ms* in the visual task, $F(1, 7) = 53.556$, $p < .001$.

These findings are consistent with the predictions of LBM assuming that bottleneck processes are still present at the end of practice even though dual-task costs are extremely reduced. The present findings extend earlier investigations of Liepelt (2006) by providing evidence of still existent bottleneck processes after prolonged practice of 12 sessions.

The findings of a latent bottleneck in the present work and those findings of Liepelt (2006) provided first evidence that is inconsistent with the assumption of Schumacher et al. (2001). Schumacher et al. assumed that the reduction of dual-task costs is evidence for a parallel component tasks processing at the end of practice. In contrast, I assume that bottleneck processes at the response selection stages are still present even after extensive dual-task practice.

Based on the present findings supporting the assumptions of LBM, I assume that this model is a candidate model to explain dual-task processing at the end of practice. Consequently, the framework of LBM seems appropriate to make specific conclusions about how practice related mechanisms within the component tasks (i.e., stage shortening) and between the component tasks (i.e., task coordination skills) improve dual-task performance. The findings about the learning mechanisms are integrated into LBM in Chapter 3.1.

3. General discussion

In the following discussion, I will present specific contributions of the learning mechanisms to the practice related dual-task cost reduction according to LBM. Additionally, I will broaden the perspective on learning mechanisms to models of skill acquisition and theories of attention control. Finally, I will provide a short outlook on future studies.

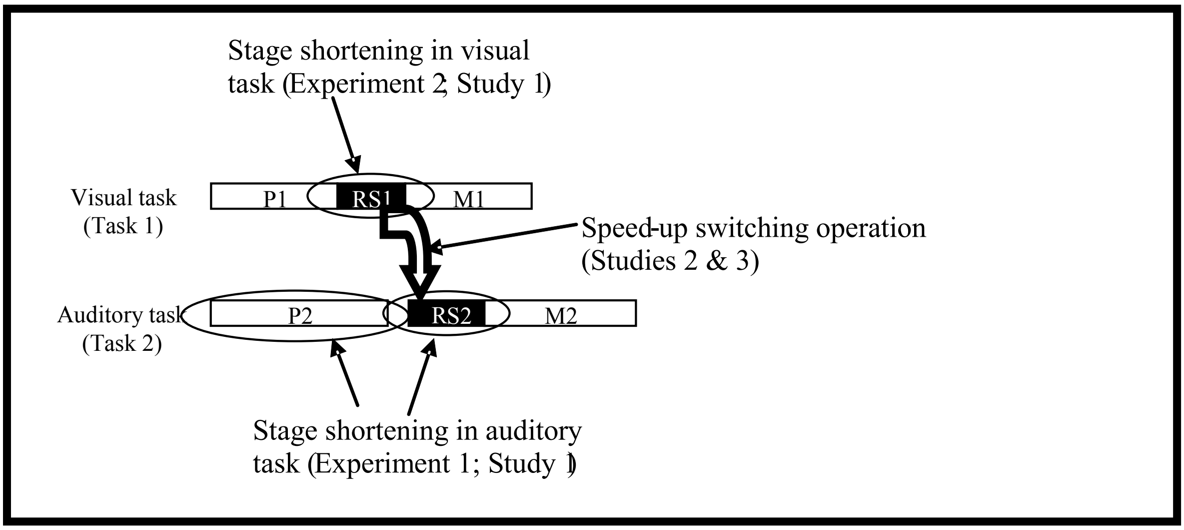

Figure 2. Integration of the assumptions about learning mechanisms into LBM. P1 and P2 indicate the perception stages; RS1 and RS2 indicate the response-selection stages; M1 and M2 indicate the motor stages. The data of Study 1 indicated that the perception stage and the response selection stage in the auditory task 2 (Experiment 1) and the response selection stage in the visual task 1 is shortened with practice. The findings of Study 2 and 3 supported the assumption of task coordination skills acquired during dual-task practice. These task coordination skills might contribute to a speed-up switching operation between the response selection stages of both component tasks.

3.1 Integration of the assumptions about learning mechanisms into LBM

In the following, I will discuss how the findings about practice related mechanisms in the present study can be integrated into the framework of LBM to explain reduced dual-task costs. The central question in this discussion is how these mechanisms contribute to the emergence of latent bottleneck processing with dual-task practice. The contributions are separately discussed for mechanisms of stage shortening within the component tasks and mechanisms of acquired task coordination skills in the following. As illustrated in Figure 2, the mechanisms of stage shortening are associated with shortened processes located at the response selection stages of the visual task and the auditory task and with a shortening of processes at the perception stage of the auditory task (Chapter 3.1.1). The mechanisms of acquired task coordination skills are associated with a speed-up switching operation between the response selection stages of both component tasks (Chapter 3.1.2).

3.1.1 Contribution of stage shortenings in the component tasks to dual-task cost reduction

How does shortening in component task processing affect the reduction of dual-task costs at the end of practice in the framework of LBM? As illustrated in Figure 1B and Figure 2, one key condition of LBM is that the response selection stages of the component tasks are extremely shortened as a result of practice. This extreme shortening reduces the likelihood of temporal overlap of these stages. Earlier studies on shortening in component tasks during dual-task practice provided evidence for unspecific stage shortening before the motor stage has started (Ruthruff et al., 2001; Sangals, et al., 2007, Van Selst et al., 1999). Thus, these studies did not support the key condition of response selection stage shortening in LBM. The findings of the present work, however, showed direct empirical evidence for stage shortening of the response selection stages in the visual and the auditory task. The evidence thus supported that key condition in the framework of LBM for the first time.

The present findings also showed that shortening at the response selection stages is not the exclusive locus of shortened component task processing with practice. This is because indications of shortened perception stage processing in the auditory task exist. In order to make conclusions about the effect of perception stage shortening on dual-task cost reduction in the framework of LBM, the consideration of task order is essential, i.e. which task is the faster and which task is the slower task in dual-task trials. Consistent across the present and previous studies applying the paradigm of Schumacher et al. (2001), mean RTs of the auditory task are increased compared to the mean RTs of the visual task. Consider Figure 1B and Figure 2, these mean RTs indicate that the visual task is the faster task in dual-task trials, i.e. Task 1, and the auditory task is the slower task in dual-task trials, i.e. Task 2. I therefore argue that the perception stage in the auditory task is completed after the end of the perception stage in the visual task (Hazeltine et al., 2002). Consequently, the perception stage shortening in the auditory task reduces the difference in the finishing times of the perception stages of the two tasks. According to LBM, this reduced difference results in an increase of the dual-task costs in the auditory task as the start of the response selection stage after the end of the perception stage is prolonged. As a consequence, the shortening at the perception stage in the auditory task is rather ineffective regarding the reduction of dual-task costs.

3.1.2 Contribution of task coordination skills to dual-task cost reduction

How do task coordination skills acquired during dual-task practice contribute to the reduction of dual-task costs at the end of practice in the framework of LBM? Thus far, Ruthruff et al. (2003) and Van Selst et al. (1999) explained the reduction of dual-task costs according to LBM with practice effects exclusively in the component tasks. However, the present work is contrary to this previous view of Ruthruff and colleagues. That is, in addition to the assumptions of practice effects in the component tasks to explain reduced dual-task costs, I will integrate assumptions about learning mechanisms associated with task coordination skills into LBM. These additional mechanisms will provide new ways of explaining the emergence of latent bottleneck processing with practice and the integration of new learning skills to explain reduced dual-task costs. Accordingly, the integration of mechanisms of task coordination skills reflects the fact that dual-task practice in addition to single-task practice is essential to promote a latent bottleneck. I therefore assume that effects of both single-task and dual-task practice are essential for the emergence of a latent bottleneck while earlier views focussed on the effects of single-task practice exclusively (e.g., Ruthruff et al., 2003; Van Selst et al., 1999).

In order to explain the specific contribution of task coordination skills to the emergence of a latent bottleneck, I make the following assumptions. I assume that task coordination skills enable an efficient coordination of the response selection stages in the two component tasks at the end of dual-task practice. As illustrated in Figure 1B and Figure 2, this efficient coordination may allow starting the response selection stage in the slower task (Task 2) immediately after the end of the response selection stage in the faster task (Task 1). After dual-task practice this immediate start of the Task 2-response selection stage leads to a reduction of the dual-task costs in that task. Conversely, I propose that the coordination of the response selection stages is less efficient when no task coordination skills are acquired as assumed for the effects of single-task practice. In this case, the response selection stage in Task 2 is not started immediately after the end of this stage in Task 1 but is postponed. This results in increased dual-task costs.

One possibility to explain the prolonged start of the response selection stage in Task 2 is the assumption of a switching operation between the response selection stages of both tasks. This operation is located after the end of the response selection stage in Task 1 and before the start of this stage in Task 2. While task coordination skills acquired during dual-task practice speed-up this switching operation, no skills are acquired during single-task practice. This leads to a prolongation of the response selection stage in Task 2 and an increase of dual-task costs in that task. Support for the assumption of a switching operation comes from a number of studies investigating dual-task processing in a non-practiced state (Band & Van Nes, 2003; De Jong, 1995; Hartley & Little, 1999; Lien, Schweickert, & Proctor, 2003; Logan & Gordon, 2001) and also one study investigating practiced dual tasks (Maquestiaux et al., 2004). The assumption of a faster start of the response selection stage in Task 2 after the end of this stage in Task 1 due to acquired task coordination skills came from the observation that the auditory task showed reduced dual-task costs after dual-task practice when compared with single-task practice. Consistent with previous studies applying the dual-task situation of

Schumacher et al. (2001) the auditory task shows longer mean RTs (Task 2) while the concurrent visual task shows shorter mean RTs (Task 1) in dual-task situations (Hazeltine et al., 2002; Tombu & Jolicoeur, 2004).

However, there is one aspect of the present experiments that could limit the conclusions about a faster start of the response selection stage in Task 2 due to acquired task coordination skills. According to this, it could be that task coordination skills reduce the dual-task costs due to a speed-up switching operation in the auditory task exclusively but that these skills do not allow for dual-task cost reduction in alternative component tasks in dual-task trials; noting that exclusively the auditory task showed longer mean RTs in all of the present experiments. In order to argue against such a limitation of assumptions about a speed-up switching operation I compared the dual-task performance after dual-task practice and after single-task practice separately for trials where the verbal response was executed second (i.e., auditory task = Task 2) and for trials where the manual response was executed second (i.e., visual task = Task 2). If the dual-task practice results in the acquisition of skills exclusive for the auditory task, one should predict reduced costs in the dual-task group only in trials with the auditory task as Task 2 but not in dual-task trials, with the visual task as Task 2. In contrast, if dual-task costs in the dual-task group are reduced in both types of dual-task trials, i.e. trials with the auditory task and the visual task as Task 2, then one should assume that task coordination skills for a speed-up switching operation are not exclusive for the auditory task and allow for improved dual-task performance in alternative component tasks.

In order to test these assumptions, I subjected the data of Experiment 1 in Study 3. I refrained to conduct inference statistical comparisons with these data as the number of dual-task trials with the visual task as Task 2 was extremely reduced (i.e., in the dual-task group: 0 – 75 trials per participant; in the single task group: 3 – 26 trials per participant). The RT analysis showed that the dual-task costs in dual-task trials with the auditory task as Task 2 amounted to *52 ms* in the dual-task group and *205 ms* in the single-task group. In dual-task trials with the visual task as Task 2, the dual-task group showed dual-task costs of *87 ms* and of *196 ms* in the single-task group.

The analyses showed reduced dual-task costs in dual-task trials on both the auditory task as well as the visual task as Task 2. These findings are inconsistent with the assumption that the dual-task practice advantage is limited to the auditory task in the present dual-task situation. However, the findings are consistent with an assumption of a speed-up switching operation in the framework of LBM that is not exclusive for the auditory task. The present analysis rather argues for a switching operation generalizable to alternative component tasks.

In sum, the present conclusion about a speed-up switching operation in LBM contrasts earlier assumptions of Ruthruff et al. (2003) and Van Selst et al. (1999). These earlier assumptions applied practice effects in the component tasks exclusively to explain dual-task cost reduction. For the first time, I integrated assumptions about task coordination skills into this model. In particular, I assumed that skills for a speed-up switching operation between the two response selection stages in dual tasks are essential for the emergence of a latent bottleneck. These skills seem to speed-up switching for different component tasks.

3.2 Broadening the perspective on learning mechanisms

3.2.1 Broadening the perspective on learning mechanisms to models of skill acquisition

After integrating the learning mechanisms into the framework of LBM, a brief discussion is warranted about how the present findings may contribute to a broader perspective of skill acquisition. This broadening can explain how these mechanisms of dual-task cost reduction are optimized during practice. In particular, I will focus on the explanation for shortened response selection stages in practiced component tasks (Study 1). For that purpose, the assumptions of two skill acquisition models are tested in the following, a task automatization model and a strategy change model.

Task automatization represents one explanation for the shortening of processes at the response selection stages. One possibility of automatization is via the development of associations that directly link stimulus and response information (Johnston & Delgado, 1993; Maquestiaux et al., 2008; Ruthruff et al., 2006). Because of the acquisition of direct links, mapping processes are extremely shortened and, consequently, will lead to a shortening of the response selection stages.

One popular model of task automatization is the Instance Model from Logan (1988). According to that model, each practice trial creates a trace of task knowledge in memory, which is called instance and which is retrieved during later trials. The next time a task is executed all traces perform a race, which determines the final speed of task processing. After prolonged practice, the increased number of traces results in a speed-up of task performance because the time for the expected fastest process becomes faster the more traces are stored in memory. Importantly, the original version of Logan's Instance Model assumes that traces store all types of stimulus and response information presented in the practiced task situations.

Alternatively to task automatization, participants may acquire skills enabling a reduction of the mental effort required to perform a task by changing from one task processing strategy to another one, leading to a shortening of response selection stage processing after practice. One particular model assuming a strategy change is the Model of Information Reduction as proposed by Haider and Frensch (1996, 1999, 2002). Information reduction applies in situations in which tasks contain both task-relevant and task-irrelevant information. In a sense, one could regard the exhaustive processing of all elements of a task in the beginning of practice (i.e., task-relevant and task-irrelevant information) to the exclusive processing of task-relevant information at the end of practice as an example of a strategy change.

At the end of practice, one first attempt to distinguish between both models of skill acquisition is to test whether improved task processing is associated with the processing of all types of stimulus and response information (as the Instance Model proposes) or whether improved task processing is not associated with the processing of all types but the exclusive processing of task-relevant information presented during practice (as the Model of Information Reduction proposes). If task processing is associated with the task-irrelevant information then manipulating this information should result in an impaired task performance. This outcome supports the assumptions of the Instance Model. In contrast, when the manipulation of the task-irrelevant information does not result in impaired task performance then task processing is not associated with that information. This outcome is consistent with the assumptions of the Model of Information Reduction.

The data in Study 1 provides an opportunity to test whether task-irrelevant stimulus and response information is processed in the visual task and the auditory task of the dual-task design of Schumacher et al. (2001) at the end of practice. In the visual task, manipulating the task-irrelevant visual stimuli (i.e., changing the form information) and manual responses (i.e., changing the response hand) revealed no increase of RTs during transfer compared to the final learning session. These findings are consistent with the assumption than no task-irrelevant visual and manual information is processed at the end of practice. Similarly, I found no increased auditory-task RTs when the verbal responses were manipulated (i.e., changing the number words). This finding is consistent with the assumption that no task-irrelevant verbal motor information is processed at the end of practice. These aspects of the current findings are consistent with the assumptions of the Model of Information Reduction and are inconsistent with the assumptions of the Instance Model. Consequently, learning mechanisms within the component tasks associated with dual-task cost reduction (in particular, response selection stage shortening) can be explained with a strategy change model; in particular, the Model of Information Reduction (see also Ahissar et al., 2001, for practice effects consistent with the assumptions of the Model of Information Reduction in an alternative dual-task situation).

However, there is occasional evidence in the data of Study 1 indicating that task-irrelevant information is processed at least to some extent at the end of practice. In particular, the manipulation of the wave-form information in the auditory task in a transfer session resulted in increased RTs in dual-task trials compared with the RTs at the end of practice. These findings suggest that processing of the auditory task is not limited to the task-relevant information and also task-irrelevant auditory information is processed after extensive practice. Thus, a marginal part of the data in the present analysis is consistent with the assumptions of the Instance Model of Logan (1988) indicating that response selection stage shortening is partially the result of task automatization.

3.2.2 Broadening the perspective on learning mechanisms to theories of attentional control

The models of skill acquisition outlined in the previous chapter (i.e., the Instance Model and the Model of Information Reduction) were associated with learning mechanisms of dual-task cost reduction in the component tasks. That means these models provide explanations about how response selection stages are shortened with practice. However, they do not allow for a sufficient explanation for learning mechanisms between the component tasks, e.g. the acquisition of task coordination skills. These learning mechanisms can be explained, however, in the framework of attentional control theories (e.g., Baddeley, 1986; Norman & Shallice, 1986). In short, these theories propose higher-order executive processes (e.g., a switching operation between two response selection stages) that control lower-order processes (e.g., mapping processes between stimulus and response information) in dual-task situations. Based on the present findings, I present 3 general characteristics of these models. First, executive processes are improved with practice. I argue that this improvement is associated with the acquisition of coordination skills. Second, these skills are acquired during dual-task practice and are not acquired during single-task practice. Third, these skills are transferable to new task situations to some extent. Nevertheless, additional empirical and theoretical work is required for a conclusive understanding and integration of assumptions about task coordination skills in the framework of attentional control theories.

3.3 Outlook for future studies

In my view, the present experimental manipulations in the dual-task situations are powerful tools to investigate processing limitations before and after practice in a broad range of research fields. For example, the manipulations allow for detailed investigations of the basic cognitive mechanisms underlying age-related deficits and their changes after practice (e.g., Glass et al., 2000; Hartley & Little, 1999; Hein & Schubert, 2004; Salthouse & Somberg, 1992; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). In detail, it is unknown whether older adults acquire task coordination skills for a speed-up switching operation during dual-task practice as assumed for younger adults (Maquestiaux et al., 2004). This question can be subject to a future learning experiment. In this experiment including older-adult participants, the dual-task performance is tested in one dual-task group and in one single-task group at the end of practice. Similar to the assumptions for younger adults, improved dual-task performance in the dual-task group compared to the performance in the single-task group would indicate the acquisition of task coordination skills during dual-task practice. In addition to the investigation of practice effects in older adults, the experimental manipulations of the present studies can be applied to investigate how human-machine interaction operates and how this interaction is optimized through practice (Fowler, Meehan, & Singhal, 2008; Harris, North, & Owens, 1979).

References

Ahissar, M., Laiwand, R., & Hochstein, S. (2001). Attentional demands following perceptual skill training. *Psychological Science*, *12(1),* 56-62.

Anderson, J. R., Taatgen, N. A., & Byrne, M. D. (2005). Learning to achieve perfect time sharing: Architectural implications of Hazeltine, Teague, & Ivry (2002*). Journal of Experimental Psychology: Human Perception and Performance*, *31,* 749–761.

Baddeley, A. D. (1986). Working Memory. Oxford, UK: Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower: Recent advances in learning and motivation, Vol. VIII, 47-90, New York: Academic Press.

Band, G. P. H., & van Nes, F. T. (2006). Reconfiguration and the bottleneck: Does task switching affect the refractory-period effect? *European Journal of Cognitive Psychology*, *18*, 593–623.

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can Training in a Real-Time Strategy Videogame Attenuate Cognitive Decline in Older Adults? *Psychology and Aging*, *23(4)*, 765-777.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: Are there age-related differences in plasticity of attentional control? *Psychology and Aging*, *20(4)*, 695-709.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2008). Transfer Effects in Task-set Cost and Dual-task Cost after Dual-task Training in Older and Younger Adults: Further Evidence for Cognitive Plasticity in Attentional Control in late Adulthood. *Experimental Aging Research*, *34*, 188-209.

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory and executive control. *Acta Psychologica*, *129*, 387-398.

Castel, A. D., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica*, *119*, 217-230.

Damos, D. L., & Wickens, C. D. (1980). The identification and transfer of timesharing skills. *Acta Psychologica*, *46(1)*, 15-39.

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

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

Dux, P., Tombu, M., Harrison, S., Rogers, B., Tong, F., & Marois, R. (2009). Training Improves Multitasking Performance by Increasing the Speed of Information Processing in Human Prefrontal Cortex. *Neuron*, *63(1)*, 127-138.

Fowler, B., Meehan, S., & Singhal, A. (2008). Perceptual-motor performance and associated kinematics in space. *Human Factors*, *50(6)*, 879-892.

Glass, J. M., Schumacher, E. H., Lauber, E. J., Zubriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (2000). Aging and the psychological refractory period: Task-coordination strategies in young and old adults. *Psychology and Aging*, *15(4)*, 571–595.

Green, C. S., & Bavelier, D. (2003). Acton video game modifies visual selective attention. *Nature*, *423*, 534-537.

Green, C. S., & Bavelier, D. (2006a). Enumeration versus object tracking: Insights from video game players. *Cognition*, *101*, 217-245.

Green, C. S., & Bavelier, D. (2006b). Effects of video game playing on the spatial distribution of visual selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32(6)*, 1465-1478.

Green, C. S., & Bavelier, D. (2007). Action video game experience alters the spatial resolution of vision. *Psychological Science*, *18(1)*, 88-94.

Haider, H., & Frensch, P. A. (1996). The role of information reduction in skill acquisition. *Cognitive Psychology*, *30*, 304-337.

Haider, H., & Frensch, P. A. (1999). Information reduction during skill acquisition: The influence of task instruction. *Journal of Experimental Psychology: Applied*, *5*, 129-151.

Haider, H., & Frensch, P. A. (2002). Why aggregated learning follows the power law of practice when individual learning does not: Comment on Rickard (1997, 1999), Delaney et al. (1998), and Palmeri (1999). *Journal of Experimental Psychology: Learning, Memory and Cognition*, *28*, 392-406.

Harris, S., North, R., & Owens, J. (1979). Human performance in time-shared verbal and tracking tasks. *Interim Report*, *Namrl*, 1259.

Hartley, A. A., & Little, D. M. (1999). Age-related differences and similarities in dual-task interference. *Journal of Experimental Psychology: General*, *128*, 417–450.

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*, 527-545.

Hein, G., & Schubert, T. (2004). Aging and Input Processing in Dual-Task Situations. *Psychology and Aging*, *19*, 416–432.

Hirst, W., Spelke, E. S., Reaves, C. C., Caharack, G., & Neisser, U. (1980). Dividing attention without alteration or automaticity. *Journal of Experimental Psychology: General*, *109*, 98–117.

Johnston, J. C., & Delgado, D. F. (1993). Bypassing the single-channel bottleneck in dual-task performance. Paper presented to the 34th annual meeting of the Psychonomic Society, Washington D.C.

Karbach, J., & Kray, J. (in press). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science*.

Klauer, K. J. (2001). Handbook of cognitive training [Handbuch Kognitives Training]. Göttingen: Hogrefe.

Kramer, A. F., Larish, J. F., & Strayer, D. L. (1995). Training for Attentional Control in Dual Task Settings: A Comparison of Young and Old Adults. *Journal of Experimental Psychology: Applied*, *1(10)*, 50-76.

Kramer, A. F., Larish, J. L., Weber, T. A., & Bardell, L. (1999). Training for executive control: Task coordination strategies and aging. In D. Gopher & A. Koriat: Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application., 617-652. Cambridge, MA US: The MIT Press.

Levy, J., Pashler, H., & Boer, E. (2006). Central Interference in Driving: Is There Any Stopping the Psychological Refractory Period? *Psychological Science*, *17(3)*, 228-235.

Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2006). Attentional limitations in doing two things at once: The search for exceptions. *Current Directions in Psychological Science*, *15(2)*, 89-93.

Lien, M.-C., Schweickert, R., & Proctor, R. W. (2003). Task switching and response correspondence in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 692-712.

Liepelt, R. (2006). Learning mechanisms enabling perfect time-sharing in dual tasks. Berlin: Shaker.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*, 492-527.

Logan, G. D., & Gordon, R. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, *108(2)*, 393-434.

Luria, R., & Meiran, N. (2003). Online order control in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 556-574.

Luria, R., & Meiran, N. (2005). Increased Control Demand Results in Serial Processing: Evidence From Dual-Task Performance. *Psychological Science*, *16(10)*, 833-840.

Luria, R., & Meiran, N. (2006). Dual route for subtask order control: Evidence from the psychological refractory paradigm. *Quarterly Journal of Experimental Psychology*, *59(4)*, 720-744.

Maquestiaux, F., Hartley, A. A., & Bertsch, J. (2004). Can practice overcome age-related differences in the psychological refractory period effect? *Psychology and Aging*, *19*, 649-667.

Maquestiaux, F., Lagu?-Beauvais, M., Ruthruff, E., & Bherer, L. (2008). Bypassing the central bottleneck after single-task practice in the psychological refractory period paradigm: Evidence for task automatization and greedy resource recruitment. *Memory and Cognition*, *36(7)*, 1262-1282.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human perception and performance*, *18*, 471-484.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. Psychological Review, *104*, 3-65.

Nino, R. S., & Rickard, T. C. (2003). Practice effects on two memory 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 behaviour. In R. J. Davidson, G. E. Schwartz, & D. Shapiro: Consciousness and self-regulation: Advances in research, Vol. 4, 1-18. New York: Plenum Press.

Oberauer, K., Demmrich, A., Mayr, U., & Kliegl, R. (2001). Dissociating retention and access in working memory: An age-comparative study of mental arithmetic. *Memory and Cognition*, *29*, 18-33.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 358-377.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. Psychological Bulletin, *116*, 220-244.

Pashler, H. (1998). The Psychology of Attention. Cambridge, MA, US: The MIT Press.

Pashler, H., & Baylis, G. (1991). Procedural learning: I. Locus of practice effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *17*, 20-32.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*, 19-45.

Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler: Attention, 155-189. Hove, UK: Psychology Press.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in RSVP task: An Attentional Blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18(3)*, 849-860.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.

Ruthruff, E., Johnston, J. C., & Van Selst, M. V. (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. V., 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*, 280-289.

Ruthruff, E., Van Selst, M., Johnston, J. C., & Remington, R. W. (2006). How does practice reduce dual-task interference: Integration, automatization, or simply stage-shortening? *Psychological Research*, *70*, 125-142.

Salthouse, T. A., & Somberg, B. L. (1982). Skilled performance: Effects of adult age and experience on elementary processes. *Journal of Experimental Psychology: General*, *111*, 176–207.

Sangals, J., Wilwer, M., & Sommer, W. (2007). Localising Practice Effects in Dual-Task Performance. *Quarterly Journal of Experimental Psychology*, *60*, 860-876.

Schubert, T. (1999). Processing differences between simple and choice reaction affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 408–425.

Schubert, T. (2008). The central attentional limitation and executive control. *Frontiers of Bisocience*, *13*, 3569-3580.

Schubert, T., & Szameitat, A. (2003). Functional neuroanatomy of interference in overlapping dual tasks: An fMRI study. *Cognitive Brain Research*, *17(3)*, 733-746.

Schumacher, E. H., Lauber, E. J., Glass, J. M., Zurbriggen, E., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (1999). Concurrent response-selection processes in dual-task performance: Evidence for adaptive executive control of task scheduling. *Journal of Experimental Psychology: Human Perception and Performance*, *25(3)*, 791-814.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, *12(2)*, 101-108.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic information processing: II Perceptual learning, automatic attending, and a general theory. *Psychological Review*, *84*, 127–190.

Sigman, M., & Dehaene, S. (2006). Dynamics of the central bottleneck: Dual-task and task uncertainty. *PLOS: Biology*, *4*, e220.

Sommer, W., Leuthold, H., & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. *Psychonomic Bulletin & Review*, *8*, 81-88.

Spelke, E. S., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition*, *4*, 215-230.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster: Attention & performance II, 276-315. Amsterdam: North-Holland.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied*, *9*, 23–32.

Szameitat, A., Lepsien, J., von Cramon, D., Sterr, A., & Schubert, T. (2006). Task-order coordination in dual-task performance and the lateral prefrontal cortex: An event-related fMRI study. *Psychological Research*, *70(6)*, 541-552.

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

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

Umiltà, C., Nicoletti, R., Simion, F., & Tagliabue, M. (1992). The cost of a strategy. *European Journal of Cognitive Psychology*, *4(1)*, 21-40.

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.

Verhaeghen, P., Steitz, D., Sliwinski, M., & Cerella, J. (2003). Aging and dual-task performance: A meta-analysis. *Psychology and Aging*, *18(3)*, 443-460.

Vince, M. A. (1948). Intermittency of control movements and the psychological refractory period. *British Journal of Psychology*, *38*, 149-157.

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.