Psychological Research
DOI 10.1007/s00426-011-0381-0

ORIGINAL ARTICLE

Investigation on the improvement and transfer of dual-task coordination skills

Tilo Strobach · Peter A. Frensch · Alexander Soutschek · Torsten Schubert

Received: 23 June 2011 / Accepted: 8 September 2011

Abstract Recent research has demonstrated that dual-task performance in situations with two simultaneously presented tasks can be substantially improved with extensive practice. This improvement was related to the acquisition of task coordination skills. Earlier studies provided evidence that these skills result from hybrid practice, including dual and single tasks, but not from single-task practice. It is an open question, however, whether task coordination skills are independent from the specific practice situation and are transferable to new situations or whether they are non-transferable and task-specific. The present study, therefore, tested skill transfer in (1) a dual-task situation with identical tasks in practice and transfer, (2) a dual-task situation with two tasks changed from practice to transfer, and (3) a task switching situation with two sequentially presented tasks. Our findings are largely consistent with the assumption that task coordination skills are non-transferable and task-specific. We cannot, however, definitively reject the assumption of transferable skills when measuring error rates in the dual-task situation with two changed tasks after practice. In the task switching situation, single-task and hybrid practice both led to a transfer effect on mixing costs.

Introduction

Executive control skills are essential for appropriate performance in complex task situations such as dual tasks. One interesting question in cognitive research is whether these skills can be improved with practice or not and to what degree these skills can be transferred to other situations. In the present research, we focus on these skill characteristics in a dual-task situation at the end of practice.

Many experiments have shown substantial performance costs in situations in which two unrelated tasks are performed concurrently relative to a situation in which the component tasks are executed separately. Performance costs, i.e., dual-task costs, are often expressed in terms of longer response times (RTs) and/or higher error rates (Pashler, 1994; Schubert, 1999; Telford, 1931; Welford, 1952). These dual-task costs are very robust, being found even for pairs of very simple tasks with no obvious input or output conflicts. For example, Schumacher et al., (2001) asked participants to perform a dual-task paradigm that consisted of a visual manual (i.e., the visual task) and an auditory verbal choice reaction task (i.e., the auditory task). In the visual task, participants responded manually by pressing keys in accordance with the spatial position of visually presented circles. In the auditory task, a low, middle, or high tone was presented and participants responded by saying either "ONE," "TWO", or "THREE", depending on the pitch of the three tones. The two component tasks were presented in both single-task and dual-task situations. In the single-task situations, either the visual or the auditory task was presented alone while in dual-task situations, one visual and one auditory stimulus were presented simultaneously (i.e., stimulus onset asynchrony, SOA of 0 ms) and participants were instructed to respond with equal priority to both stimuli. Dual-task costs, measured by reaction times (RTs) in dual-task situations minus RTs in single-task situations, were relatively high at the beginning of practice.

T. Strobach (✉) · A. Soutschek · T. Schubert
Department Psychology, Ludwig-Maximilians-University, Munich, Leopoldstr. 13, 80802 Munich, Germany
e-mail: tilo.strobach@psy.lmu.de

T. Strobach · P. A. Frensch · T. Schubert
Humboldt-University, Berlin, Berlin, Germany

Published online: 27 September 2011

However, after five sessions of single-task and dual-task practice, dual-task costs were extremely reduced (in fact, they were not significantly different from zero). The finding of an extreme reduction of dual-task costs with extended practice in the Schumacher et al. (2001) study has been corroborated by a number of subsequent studies that used concurrent choice reaction time tasks (e.g., Hazeltine, Teague, & Ivry, 2002; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff et al. 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006; Van Selst, Ruthruff, & Johnston, 1999), working memory updating tasks (Oberauer & Kliegl, 2004), and memory retrieval tasks (Nino & Rickard, 2003).

The empirical evidence for extreme dual-task cost reduction after practice is thus convincing. On the other hand, the cognitive mechanisms underlying this reduction of dual-task costs remain relatively unclear. In the present research, we focus on skills that are assumed to allow for a practice-related improvement of the coordination of two simultaneously presented component tasks, which we call task coordination skills (Kramer, Larish, & Strayer, 1995; Maquestiaux, Hartley, & Bertsch, 2004). Specifically, we consider task coordination skills as mechanisms that control and coordinate two simultaneously ongoing task streams (Damos & Wickens, 1980). Because a practice-related improvement of task coordination skills is specifically related to mechanisms regulating the relation between two component tasks, it needs to be distinguished from mechanisms leading to a practice-related improvement of the single component tasks (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980) such as a practice-related reduction of dual-task costs by (1) shortening capacity limited processes in the single component tasks (e.g., Dux et al., 2009; Kamienkowski, Pashler, Sigman, & Dehaene, 2011; Pashler & Baylis, 1991; Ruthruff et al., 2006; Sangals, Wilwer, & Sommer, 2007; Van Selst et al., 1999), (2) automatization and simultaneous performance of these processes (e.g., Johnston & Delgado, 1993; Maquestiaux, Laguẽ-Beauvais, Ruthruff, & Bherer, 2008; Ruthruff et al., 2006; Shiffrin & Schneider, 1977), or (3) the integration and combination of two separate component tasks into one single task (e.g., two 3-choice tasks become one single task that maps nine possible stimulus combinations onto nine possible response combinations; Hazeltine et al., 2002). The account of the present study holds that a practice-related reduction of dual-task costs can additionally be achieved through a practice-related improvement of task coordination skills. We will come back to the mechanisms of practice-related improvement of dual-task performance within the single component tasks and differences to mechanisms of task coordination skills in the "General discussion".

Acquisition of improved task coordination skills during practice

Hirst et al. (1980) and Kramer et al. (1995) proposed two corollaries of improved task coordination skills. First, these skills are acquired during dual-task, but not during single-task practice. In particular, while dual-task practice may lead to a more efficient coordination of two simultaneously performed task streams, the pure practice of single component tasks does not. Second, once acquired, improved task coordination skills should be independent from the practiced task situation. Consequently, task coordination skills acquired in a particular dual-task situation may be transferred to other unpracticed situations (see also Bherer et al., 2005, 2008; Maquestiaux et al., 2004; Spelke, Hirst, & Neisser, 1976). While Liepelt, Strobach, Frensch, and Schubert (2011) recently provided remarkable evidence for the acquisition of improved task coordination skills in dual-task situations (see also Oberauer & Kliegl, 2004), there is no sufficient evidence for the transferability of these skills. The present study continues on that research line and aims at elucidating the issue of the transferability of task coordination skills.

In their study, Liepelt et al. (2011) investigated practice effects with the dual-task situation of Schumacher et al. (2001) including one visual and one auditory task. To test the acquisition of task coordination skills in their Experiment 1, the authors compared the dual-task performance of two groups of participants experiencing dual-task practice in different degrees during an initial practice phase: (1) a hybrid practice group which experienced dual-task practice in addition to single-task practice, and (2) a single-task practice group experiencing only practice with the single tasks alone. In fact, after seven sessions of hybrid practice, dual-task performance in an eighth transfer session was improved when compared to the dual-task performance after seven sessions of single-task practice. This improvement was particularly evident in reduced dual-task RTs in the auditory task. In the task situation of Schumacher et al., the auditory task typically represents the "longer" component task (i.e., higher RTs) while the visual task is the "shorter" component task (i.e., lower RTs) in single-task and dual-task situations. Based on the findings of a hybrid practice advantage in this longer auditory task, Liepelt et al. proposed a increased switching operation as a result of improved task coordination skills after hybrid practice. This switching operation may be located after the end of the response selection stage in the shorter visual task and before the start of that stage in the longer auditory task (Band & van Nes, 2006; Lien, Schweickert, & Proctor, 2003). Due to this particular location, a shortening of a switching operation after hybrid practice affects dual-task RTs in that longer task, while there is no effect on the shorter visual task.

As a further important finding, Liepelt et al. (2011) provided preliminary though not conclusive evidence about the transferability of task coordination skills after hybrid practice. For that purpose, they conducted two transfer experiments in which they changed specific task characteristics of the visual task (Experiment 2) or the auditory task (Experiment 3) after practice. In Experiment 2, the authors changed the location mapping to a size mapping in the visual task, while the auditory task remained constant in Session 9 after eight sessions of practice. As a result, hybrid practice resulted in improved dual-task performance when compared to the performance after single-task practice. Similarly, hybrid practice resulted in improved dual-task performance in Experiment 3 in which the visual task remained constant and the mapping in the auditory task was changed from compatible to incompatible mapping rules between tones and number of words after eight sessions of practice in Session 9. Thus, in both transfer experiments (i.e., including either a changed visual task or a changed auditory task), hybrid practice of the Schumacher et al. (2001) task situation particularly resulted in reduced RTs of the auditory task in dual-task situations. As it stands, these data might be interpreted as evidence for a possible independence of improved task coordination skills from the specific characteristics of either the visual or the auditory task.

However, the findings of Liepelt et al. (2011) are not unequivocal regarding the issue of the transferability of the acquired skills. This is because according to Hazeltine et al. (2002) and Ruthruff et al. (2006), improved skills acquired during dual-task practice may also be tied to the specific characteristics of practiced dual-task situations. That is, these skills may be associated with the specific component tasks in dual tasks. According to this assumption, the hybrid practice advantage in Liepelt et al. (2011) Experiments 2 and 3 may follow from the unchanged task that remained constant while the other task had been changed from learning to transfer. That is, acquired task coordination skills may by tied to either of the two tasks in a dual-task situation (in the case of Liepelt et al.: the visual or the auditory task) and only one constant task after practice might be sufficient for an application of skills. The experiments are, therefore, not yet fully conclusive about a possible independence and transferability of the acquired task coordination skills. To conclude that hybrid practice leads to an acquisition of task-independent skills, evidence is needed that task coordination skills are not tied to specific characteristics of both component tasks (Bherer et al., 2008) and not only to one component task as shown by Liepelt et al.

The present study

The aim of the present study was to test whether, once acquired during practice with the Schumacher et al. (2001) paradigm, improved task coordination skills are truly independent from the specific characteristics of both practiced tasks and transferable to alternative task situations or whether these skills are specific for the practiced tasks. We applied the paradigm of Schumacher et al. because of its optimal conditions to investigate improved dual-task performance and acquired task coordination skills by the inclusion of a mix of single and dual-task situations (Kramer et al., 1995). This mix is essential because the exclusive inclusion of dual-task (e.g., Ruthruff et al., 2006) or of only single-task situations (e.g., Liepelt et al., 2011; Oberauer & Kliegl, 2004) did not prove to be sufficient for an improvement of dual-task performance and/or for the acquisition of task coordination skills (also see "General discussion").

We assessed the transferability of task coordination skills for the task situation of Schumacher et al. (2001) with three tests after two different types of task practice: hybrid practice, including combined single and dual tasks, as well as single-task practice (Liepelt et al., 2011). In Test 1, a dual-task transfer situation identical to the preceding practice situation is presented, while in Test 2 we presented a dual-task transfer situation with two changed component tasks after practice (Experiment 1). Test 3 includes a task switching situation (Monsell, 2003) with two tasks presented sequentially (Experiment 2). Although task switching situations differ structurally from dual tasks (i.e., sequential vs. simultaneous task presentation), similar executive control skills may be involved in both types of task situations and a transfer of skills from one to the other might be plausible (Lien et al., 2003; Liepelt et al., 2011; Strobach, Liepelt, Schubert, & Kiesel, in press; for more details see Experiment 2). Unlike the task switching test, Test 2 allows assessing transfer to a situation that is structurally similar to the practice situation (both are dual-task situations); thus, Tests 2 and 3 allow checking the range of potential transfer effects (with Test 3 examining further transfer effects than Test 2).

We can examine two hypotheses when applying these tests. According to the *hypothesis of task-specific skills*, the acquired task coordination skills are task-specific for the practiced dual-task situation and not transferable to alternative task situations. Here, we expect a dual-task performance advantage after hybrid practice compared with single-task practice in Test 1, while there should be no performance advantage in Test 2 and Test 3. According to the *hypothesis of task-unspecific skills,* acquired task coordination skills are not task-specific for the practiced situation and are transferable to alternative task situations. We would expect a dual-task performance advantage after hybrid practice in Test 2, if task coordination skills are transferable to the dual-task transfer situation and if the hypothesis of task-unspecific skills would be true. If this hypothesis would be true and task coordination skills are transferable even to structurally dissimilar task situations such as task switching, then we should find improved task switching performance in Test 3 after hybrid practice in contrast to the results of single-task practice. Examinations of the hypotheses of task-specific and task-unspecific skills were the objectives in Experiment 1 and 2.

Experiment 1

There are two research aims for Experiment 1: the first aim was to test the acquisition of improved task coordination skills after two different types of practice, hybrid and single-task practice, with the identical visual and the auditory tasks of the paradigm of Schumacher et al. (2001). Participants in the *hybrid group* practiced the two tasks in single task and dual task conditions for eight sessions. Participants in the *single-task practice group* practiced the two component tasks in single-task blocks for seven sessions and performed single tasks and dual tasks in Session 8. Session 8 was thus identical for the two groups, and allowed for an assessment of dual-task performance in the practiced visual and auditory tasks. If task coordination skills are acquired during hybrid practice, we would expect improved dual-task performance after hybrid when compared with single-task practice in Session 8. This would be consistent with the hypothesis of task-specific skills.

The second aim of Experiment 1 was to test whether the improved skills acquired during hybrid practice may transfer to a dual-task situation with two changed tasks instead of only one task as in Liepelt et al. (2011) (i.e., *dual-task test for unspecific skills*). For that purpose, we changed the task characteristics of the visual and the auditory component tasks after eight sessions of hybrid practice (i.e., in the hybrid practice group) and after eight sessions of single-task practice (i.e., in a new *single-task transfer group*) in a further transfer phase of the experiment, i.e., in Session 9. In that session, we changed the stimulus–response mapping of the visual task as compared to the mapping during practice, similarly as in Liepelt et al. (Experiment 2); participants now responded to stimuli of different size (small, medium, large stimulus) with finger key presses. We also changed the stimuli in the visual task; instead of circles, we presented triangles in the transfer session in order to prevent that task coordination skills may be tied to the practiced visual stimuli. For the auditory task, we introduced an incompatible mapping while participants had practiced a compatible mapping during learning. We introduced this particular type of manipulation because we aimed to apply a manipulation, which should lead to RT increases in the changed auditory task, which are numerically in a similar range as the changes in the visual task (see also Liepelt et al. 2011, Experiment 3). Prior experimentation in Liepelt et al. indicated that a change of the mapping rule from compatible to incompatible in the auditory task without additional change of the stimuli would lead to an increase of the RTs in the changed auditory task ($M = 119$ ms), which is comparable to the amount of the RT increase of the visual task with changed mapping rules and stimuli ($M = 126$ ms).

Session 9 (with changed component tasks after practice) included single-task and dual-task conditions and allowed for an assessment of the dual-task performance in the hybrid group and the single-task transfer group. If task coordination skills are task-unspecific and transfer to the dual-task situation in this session, we should find improved dual-task performance after hybrid when contrasted with single-task practice in Session 9; this would be consistent with the hypothesis of task-unspecific skills while the hypothesis of task-specific skills would predict no advantage of the hybrid practice group in this session.

Importantly, the two component tasks were presented equally often in the two practice conditions, hybrid and single-task practice, allowing for a similar level of component task processing skill after practice (Kramer et al., 1995). In order to control the potential effects of differences in the initial dual-task performance, this performance was tested at the beginning of practice in both single-task groups (i.e., the single-task practice and single-task transfer groups) and the hybrid group and used as baseline performance when assessing dual-task performance after practice (see Table 1).

Methods

Participants

Participants were randomly assigned to one of the three experimental groups: the hybrid group, the single-task transfer group, and the single-task practice group. The hybrid group included 10 participants (5 female) with a mean age of $M = 23.7$ years (SD = 3.3 years) and an age range from 19 to 29 years. Ten participants (five females) were included in the single-task transfer group with a mean age of $M = 26.2$ years (SD = 4.4 years, age range from 19 to 32 years). The single-task practice group included eight participants (four female) with a mean age of $M = 25.1$ years (SD = 3.9 years) and an age range from 18 to 31 years.

Participants were contacted through electronic mails. Mail addresses were taken from a database at the Department of Psychology at Humboldt-University Berlin. All participants had normal or corrected to normal vision and were not informed of the purpose of the experiment. They

Table 1 Overview of practice and transfer procedure completed by the four experimental groups (i.e., hybrid group, single-task practice group, single-task transfer group, non-learner group) in Experiments 1 and 2

Experiment 1	Pre-test: dual-task test for unspecific skills (first four blocks in Session 2)	Practice	Post-test: skill acquisition test (Session 8)	Post-test: dual-task test for unspecific skills (Session 9)
Hybrid group	Single and dual tasks	Single and dual tasks (Sessions 1–8)	Single and dual tasks	Single and dual tasks
Single-task practice group	Single and dual tasks	Single tasks (Sessions 1–7)	Single and dual tasks	
Single-task transfer group	Single and dual tasks	Single tasks (Sessions 1–8)		Single and dual tasks
Experiment 2	Pre-test: task switching test for unspecific skills		Post-test: task switching test for unspecific skills	
Hybrid group	Switch, repetition, and single tasks		Switch, repetition, and single tasks	
Single-task transfer group	Switch, repetition, and single tasks		Switch, repetition, and single tasks	
Non-learner group	Switch, repetition, and single tasks		Switch, repetition, and single tasks	

were paid for participation at a rate of 8 € per session plus performance-based bonuses (see "Design and procedure").

Apparatus

Visual stimuli were presented on a 17-inch color monitor and auditory stimuli were presented via headphones, which were connected to a Pentium I IBM-compatible PC. The RT for manual responses was recorded with a button box and the RT of verbal responses was recorded via a voice key connected to the experimental computer. The experiment was controlled by the software package ERTS (*Experimental Runtime System*; Beringer, 2000).

Stimuli and component tasks

Practice and skill acquisition test

During practice and the skill acquisition test, participants conducted two choice RT tasks. In the visual task, participants responded manually by pressing a spatially compatible key with the index, middle, or ring finger of their right hand to white circles appearing at the left, central, or right position arranged horizontally on the computer screen. In visual single-task trials, three white dashes served as placeholders for the possible positions of the visual stimuli. These dashes appeared as a warning signal 500 ms before the visual stimulus was presented. The stimulus remained visible until the participant responded or a 2,000 ms response interval had expired. In the auditory task, participants responded to sine wave tones presented at frequencies of either 300, 950, or 1,650 Hz by saying "ONE", "TWO", or "THREE" (German: "EINS", "ZWEI", or "DREI"), respectively. An auditory single-task trial started with the presentation of three dashes on the computer screen. After an interval of 500 ms, the tones were presented for 40 ms. The trial was completed when the participant responded verbally or a 2,000 ms response interval had expired. To analyze the accuracy of each response, the experimenter recorded the verbal responses. After correct responses in the visual and in the auditory task, the RTs were presented for 1,500 ms on the screen. Following incorrect responses, the word "ERROR" (German: "FEHLER") appeared. A blank interval of 700 ms preceded the beginning of the next trial in both component tasks.

Dual-task trials included the visual and the auditory task. These trials were identical to single-task trials with the exception that a visual and an auditory stimulus were presented simultaneously (SOA = 0 ms) and participants responded to both stimuli with equal emphasis.

Dual-task test for unspecific skills

During the dual-task test for unspecific skills, two changed versions of the visual and the auditory choice RT tasks were presented in single- and dual-task trials. Both tasks differed from the practice component tasks as follows: In the visual task, participants responded to the size of large-, medium-, and small-sized triangles appearing at the central position of the computer screen. In the auditory task, participants responded incompatibly to sine wave tones of frequencies of 300, 950, or 1,650 Hz by saying "TWO", "ONE", or "THREE" (German: "ZWEI", "EINS", "DREI"), respectively. Similar to the practice sessions, three white dashes appeared as a warning signal 500 ms before the visual and/or auditory stimuli were presented.

Design and procedure

Hybrid group

As illustrated in the overview in Table 1, this group performed hybrid practice, i.e., combined single- and dual-task practice in Sessions 1–8. In Session 9, this group performed single- and dual-task trials with two changed tasks. All sessions were conducted on successive days (excluding weekends).

During hybrid practice, there were single-task trials and dual-task trials. Single tasks of the visual or the auditory task were included into single-task blocks of 45 trials. In contrast, 18 dual-task trials were included into dual-task blocks combined with 30 mixed single-task trials, 15 of the visual task and 15 of the auditory task. These mixed single-task trials helped to ensure that participants were equally prepared for both tasks in dual-task blocks; alternatively, they could prepare for only one task that is executed first in dual-task trials. Participants were instructed to respond to both stimuli as quickly and accurately as possible during all blocks. Response order was free.

In Session 1, participants of the hybrid group performed six visual and six auditory single-task blocks that were presented in alternating order. Half of the participants started with a visual single-task block and the other half with an auditory single-task block. Session 2 included six single-task blocks (three visual and three auditory task blocks) and eight dual-task blocks. After two initial single-task blocks (one visual and one auditory single-task block), sequences of two dual-task blocks and one single-task block followed; the type of single-task blocks was alternated. The order of blocks (first visual or auditory task block) was counterbalanced across participants. The design in Sessions 3–9 was identical to that in Session 2 but these sessions included two additional dual-task blocks at the end. While we presented the practice component tasks from Sessions 1–8, we changed to the transfer component tasks in Session 9.

Reward was given in the form of a monetary performance-based payoff to maximize participants' motivation for achieving accurate and fast performance (see also Schumacher et al., 2001; Tombu & Jolicoeur, 2004). The payoff matrix was based on an adaptive comparison between participant's performance in a given trial (i.e., current RT) and a reference RT, the so-called *target time*. The experiment started with a target time of 2,000 ms, which was then adjusted after each block separately for each participant and task condition (single- vs. dual-task condition). Target times were calculated using the mean RT of single-task trials in single-task blocks and the mean RT of dual-task trials in mixed blocks. Depending on their individual performance improvement, participants could earn more or less money. When participants' mean RT for a given block was slower than the target time, but still in a range of 50–100 ms above the target time, they received 10 cents in addition for that block. When the mean RT was in a range of 0–50 ms above the target time, they received 25 cents. Importantly, when the RT of the ongoing block was faster than the target time, they received 50 cents and the RT of the ongoing block served as the new target time for the upcoming blocks. The mean RT of the current block and the target time were presented at the end of each block. Bonus payments were also made on the basis of accuracy rates: one additional cent was given for each correct response and 5 cents were deducted for each incorrect response. Participants earned separate bonuses for the two tasks (visual and auditory) as well as for single and mixed blocks.

Single-task practice group

The dual-task performance after practice in the single-task practice group served as a control measure for the dual-task performance after hybrid practice; the comparison of this performance in both groups enables the assessment of improved task coordination skills. As illustrated in the overview in Table 1, the experimental procedure in the single-task practice group was similar to the hybrid group with the exception that this group of participants performed single tasks exclusively in Sessions 1–7 and performed no Session 9.

The details of single-task practice are the following: the single-task practice group mainly received single-task blocks for seven sessions. To keep the number of stimulus contacts between dual-task conditions (in the hybrid group) and single-task conditions constant, one dual-task trial was replaced by one single-task trial of each task. Consequently, we had single-task blocks with 45 trials (short blocks) but also single-task blocks with 66 trials (long blocks). Session 1 was identical to the hybrid group. Session 2 included 12 single-task blocks (6 visual and 6 auditory single-task blocks) and two dual-task blocks; these dual-task blocks were included to analyze initial dual-task performance in the single-task practice group at the beginning of practice and to match this performance between practice groups. In Session 2, these two initial dual-task blocks were introduced after two short single-task blocks. Then, sequences of one short and two long single-task blocks followed. In Sessions 3–7, we presented 16 single-task blocks (8 visual and 8 auditory single-task blocks). After two initial short single-task blocks, sequences of two long single-task blocks and one short single-task block followed. In Sessions 2–7, blocks with the visual and auditory task were alternated and the first type of block (either visual or auditory task) was counterbalanced between subjects. The following Session 8 was identical to this session in the hybrid group.

Single-task transfer group

The performance in a changed dual-task situation after practice in the single-task transfer group served as a control measure for this performance after hybrid practice; the comparison of this performance between both groups enables investigating task-unspecific coordination skills. As illustrated in the overview in Table 1, the experimental procedure in the single-task transfer group included exclusively single-task practice in Sessions 1–8. This type of practice was identical to the procedure in the single-task practice group in these sessions. Session 8 resembled the previous Sessions 3–7. The subsequent Session 9 was identical to this session in the hybrid group with the inclusion of the transfer component tasks; we presented the practice component tasks in all the previous sessions.

Results and discussion

The Results section is structured as follows: First, the practice findings in the hybrid group are presented, separately for both the visual and the auditory task. Then, we present the analyses that focus on the acquisition of task coordination skills during hybrid practice (i.e., skill acquisition test); that is, we compare the single- and dual-task performance in Session 8 between the hybrid and single-task practice groups. Following, we present analyses on the transfer of potentially acquired skills (i.e., dual-task test for unspecific skills). In this analysis, we compare the single-task and dual-task performance of Session 9 between the hybrid and the single-task transfer groups. Our primary indicator of dual-task performance in both tests is the dual-task performance costs in dual-task trials compared with single-task trials of single-task blocks (Liepelt et al., 2011; Tombu & Jolicoeur, 2004).

Hybrid practice

To analyze the hybrid practice findings, we entered the RT data and the error data into separate repeated-measures ANOVAs with SESSION (Sessions 2–8) and TRIALTYPE (single-task trials, mixed single-task trials, & dual-task trials) as within-subject factors. From the RT data, we excluded 5.8% of error trials. Participants made faster manual responses in the visual tasks than verbal responses in the auditory task in 95.2% of the dual-task trials; this ratio was consistent across all practice sessions.

The RTs of the *visual task*, illustrated in Fig. 1a, declined considerably during practice, $F(6, 54) = 50.126$, $p < .001$, and they differed for the different types of trials, $F(2, 18) = 31.582$, $p < .001$, indicating the highest RTs in dual-task trials ($M = 302$ ms), followed by mixed single-task trials ($M = 272$ ms), and single-task trials ($M = 252$ ms), all *ps* $< .001$. A significant interaction of SESSION and TRIALTYPE, $F(12, 108) = 13.132$, $p < .001$, showed that the practice effect for dual-task performance exceeded this effect for the single tasks. Dual-task costs (i.e., RTs dual-task trials minus RTs single-task trials) of $M = 120$ ms in Session 2, $t(9) = 4.913$, $p < .001$, were reduced to $M = 27$ ms in Session 8, $t(9) = 4.158$, $p < .01$.

Error rates, as illustrated in Table 2a, were higher in single-task trials ($M = 4.2\%$) than in mixed single-task ($M = 1.4\%$) and dual-task trials ($M = 2.4\%$), $F(2, 18) = 12.824$, $p < .001$, and these rates were increased at the end of practice ($M = 3.1\%$) compared with the beginning of practice ($M = 2.3\%$), $F(6, 54) = 3.488$, $p < .01$. The interaction of SESSION and TRIALTYPE, $F(12, 108) = 4.469$, $p < .001$, indicated that learning effects differed between the types of trials. While no dual-task error costs (i.e., error rates in dual-task trials minus error rates in single-task trials) were present at the beginning of practice, $t(9) = 1.696$, $p > .12$, single-task trials showed higher error rates than dual-task trials at the end of practice, $t(9) = -3.061$, $p < .05$. This single-task disadvantage at the end of practice is consistent with previous studies using a similar dual-task situation (Hazeltine et al., 2002; Schumacher et al., 2001; Tombu & Jolicoeur, 2004), and can be explained by a reduced degree of attentiveness in single-task trials due to reduced processing demands in the visual task (Hazeltine et al., 2002). Thus, we cannot exclude a speed–accuracy trade-off in dual-task practice effects of the visual task.

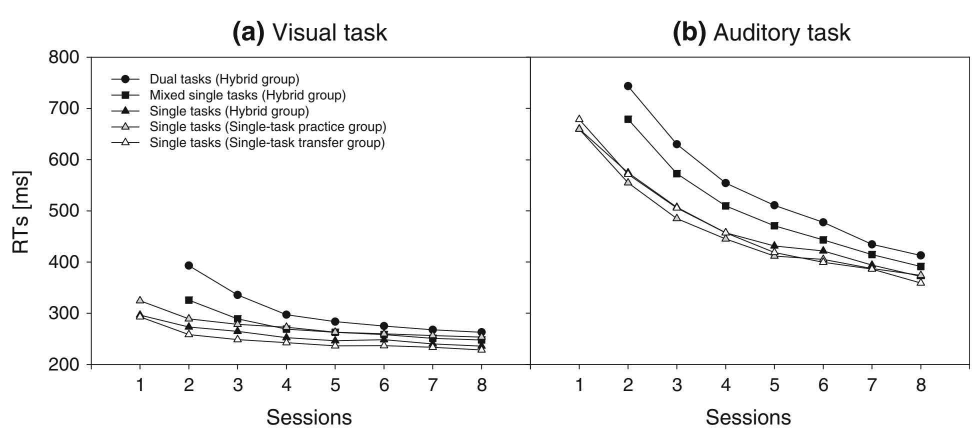

Fig. 1 Single-task RTs (in ms) of the hybrid, single-task practice, and single-task transfer groups plus mixed single-task and dual-task RTs of the hybrid group during Sessions 1–8 in Experiment 1. **a** Visual task, **b** auditory task

Table 2 Single-task error rates (in percent) of the hybrid, single-task practice, and single-task transfer groups plus mixed single-task and dual-task error rates of the hybrid group during Sessions 1 to 8 in Experiments 1 and 2

(A) Visual task

Hybrid group				Single-task practice group	Single-task transfer group
Session	Single tasks	Mixed single tasks	Dual tasks	Single tasks	Single tasks
1	1.9			0.8	1.8
2	2.4	0.3	4.2	1.6	2.5
3	3.2	0.9	2.1	2.0	4.0
4	3.9	1.4	2.1	2.5	4.8
5	4.1	1.5	2.0	2.8	4.9
6	4.7	1.2	1.6	3.2	5.7
7	5.9	2.3	2.4	3.4	5.8
8	5.1	1.8	2.5	3.5	6.0

(B) Auditory task

Hybrid group				Single-task practice group	Single-task transfer group
Session	Single tasks	Mixed single tasks	Dual tasks	Single tasks	Single tasks
1	5.6			5.1	5.6
2	4.2	3.9	6.5	2.4	4.1
3	3.3	3.3	5.8	2.4	3.0
4	2.0	3.1	3.9	2.7	3.3
5	3.1	2.5	5.4	2.6	3.5
6	6.2	4.3	5.7	2.6	4.6
7	5.1	4.5	5.7	3.1	4.4
8	3.9	3.4	5.6	4.1	3.8

As illustrated in Fig. 1b, *auditory task* data showed a dual-task practice effect. RTs were lower at the end ($M = 392$ ms) than at the beginning of practice ($M = 665$ ms), $F(6, 54) = 108.590$, $p < .001$, they were lower in single-task trials ($M = 451$ ms) followed by mixed single-task ($M = 497$ ms) and dual-task trials ($M = 538$ ms), all $ps < .001$, $F(2, 18) = 59.298$, $p < .001$. A significant interaction of SESSION and TRIALTYPE, $F(12, 108) = 15.004$, $p < .001$, demonstrated a larger practice effect for dual tasks compared to single tasks. Dual-task costs decreased from $M = 169$ ms in Session 2, $t(9) = 8.207$, $p < .001$, to dual-task costs of $M = 41$ ms in Session 8, $t(9) = 6.993$, $p < .001$. Error rates were higher in dual-task trials ($M = 5.5\%$) than in single-task ($M = 4.0\%$) and mixed single-task trials ($M = 3.6\%$), $F(2, 18) = 11.242$, $p < .001$ (Table 2b). There was no effect of and interaction with SESSION, $F(6, 54) = 1.468$, $p > .21$ and $F(12, 108) = 1.308$, $p > .23$, respectively.

In sum, we found that practice of single-task and dual-task conditions strongly improved dual-task performance in the dual-task paradigm of Schumacher et al. (2001). There was, however, no complete elimination of dual-task costs in the final practice Session 8. This is not consistent with some previous studies that applied this paradigm and showed no statistical evidence for dual-task costs at the end of practice (Hazeltine et al., 2002; Schumacher et al., 2001). However, the finding of residual costs is in accordance with other studies applying the same paradigm (Liepelt et al., 2011; Strobach, Frensch, & Schubert, 2008; Tombu & Jolicoeur, 2004).[1]

[1] In fact, dual-task RT costs in practice Session 8 of the study of Tombu and Jolicoeur (2004); visual task: 26 ms; auditory task: 40 ms) were very similar to the present costs (visual task: 27 ms; auditory task: 41 ms). These findings show possible boundary conditions to obtain perfect dual-task performance in this paradigm. The finding of residual dual-task costs in the present study might be due to the use of separate deadlines for dual-task and single-task conditions taken as the basis of the financial payoff matrix. This procedure might maintain strong motivation for both single-task trials and dual-task trials until the end of practice (Tombu & Jolicoeur, 2004). In contrast, Schumacher et al. (2001) exclusively used the performance deadline of the single-task trials presented during the mixed blocks to award financial payoff in both single-task and dual-task trials during practice (see also Hazeltine et al., 2002). The Schumacher procedure might increase effects of mobilized effort in dual-task trials as compared to single-task trials. As a result of this, one should find a greater reduction of RTs in dual tasks than in single tasks during practice. This difference in deadline procedures between studies might explain the finding of non-significant dual-task costs in the study of Schumacher and colleagues in contrast to the small residual dual-task costs we found at the end of practice.

Skill acquisition test

We compared the single-task and dual-task performance at the beginning of practice (i.e., pre-test) and at the end of practice (i.e., post-test) in the hybrid and the single-task practice groups. Improved dual-task performance in the hybrid group, compared to the single-task practice group, during post-test would point to the acquisition of improved task coordination skills if it cannot be explained by different performance levels during pre-test. For the pre-test comparison, we analyzed the dual-task performance by comparing the RTs in the first two single-task blocks with that of the dual-task trials in the two following mixed blocks in Session 2. The data of Session 8 (in which both the single-task practice and the hybrid groups performed single and dual tasks) served as the post-test measure for the performance at the end of practice. We performed mixed-measures ANOVAs on the RTs and error rate data with the within-subject factors TESTPHASE (pre-test vs. post-test) and TRIALTYPE (single-task trials vs. dual-task trials), and the between-subject factor GROUP (hybrid group vs. single-task practice group).

In the *visual task*, there was no advantage in the RT data and no evidence for the acquisition of improved task coordination skills after hybrid practice. This lacking effect is demonstrated by a non-significant effect of and interaction with GROUP, $Fs(1, 16) < 2.909$, $ps > .11$. Instead, we only found decreased RTs from pre-test ($M = 375$ ms) to post-test ($M = 269$ ms), $F(1, 16) = 93.491$, $p < .001$, and from dual-task ($M = 374$ ms) to single-task trials ($M = 270$ ms), $F(1, 16) = 102.970$, $p < .001$. The interaction of TESTPHASE and TRIALTYPE was also significant, $F(1, 16) = 55.464$, $p < .001$.

The corresponding analysis of the error rates showed an interaction of TESTPHASE and TRIALTYPE, $F(1, 16) = 27.842$, $p < .001$, revealing higher dual-task error rates ($M = 7.0\%$) compared to single-task error rates ($M = 2.2\%$) during pre-test, $t(17) = 3.542$, $p < .01$ (Fig. 2b). During post-test, error rates in dual-task trials ($M = 2.0\%$) were lower than in single-task trials ($M = 4.3\%$), $t(17) = 4.526$, $p < .001$; this dual-task advantage corroborates the separate analysis of the data in the hybrid group. What is important for the question concerning the acquisition of improved task coordination skills is that for the visual task we found no significant dual-task specific advantage of hybrid practice over single-task practice.

For the *auditory task*, however, RT findings indicate the acquisition of improved task coordination skills that are consistent with the hypothesis of task-specific skills (see also Liepelt et al., 2011). In fact, we found a three-way interaction between TESTPHASE, TRIALTYPE, and GROUP, $F(1, 16) = 6.914$, $p < .05$. As illustrated in Fig. 2a, this interaction reflects a dual-task specific advantage of hybrid practice over single-task practice exclusively in the post-test analysis. Post-test RTs in the dual-task trials were significantly reduced in the hybrid group ($M = 425$ ms) relative to the RTs of the single-task practice group ($M = 568$ ms), $t(16) = 2.720$, $p < .05$. In contrast, post-test RTs were identical in single-task trials for the two groups of participants so were single- and dual-task RTs during pre-test, $ts(16) < 1$. Thus, improved dual-task performance in the hybrid group at post-test cannot be explained by different component task processing skills after practice and different initial single-task and dual-task performance levels. We also found generally increased RTs during pre-test ($M = 752$ ms) compared to post-test ($M = 434$ ms), $F(1, 16) = 220.886$, $p < .001$, and in dual-task trials ($M = 670$ ms) compared with single-task trials ($M = 497$ ms), $F(1, 16) = 124.601$, $p < .001$. Additionally, TESTPHASE interacted with GROUP, $F(1, 16) = 5.826$, $p < .05$, as well as with TRIALTYPE, $F(1, 16) = 26.059$, $p < .001$.

The corresponding analysis of the error rates in the auditory task indicated lower error rates during post-test ($M = 5.1\%$) than during pre-test ($M = 7.4\%$), $F(1, 16) = 4.014$, $p < .062$, and for single-task ($M = 4.5\%$) than dual-

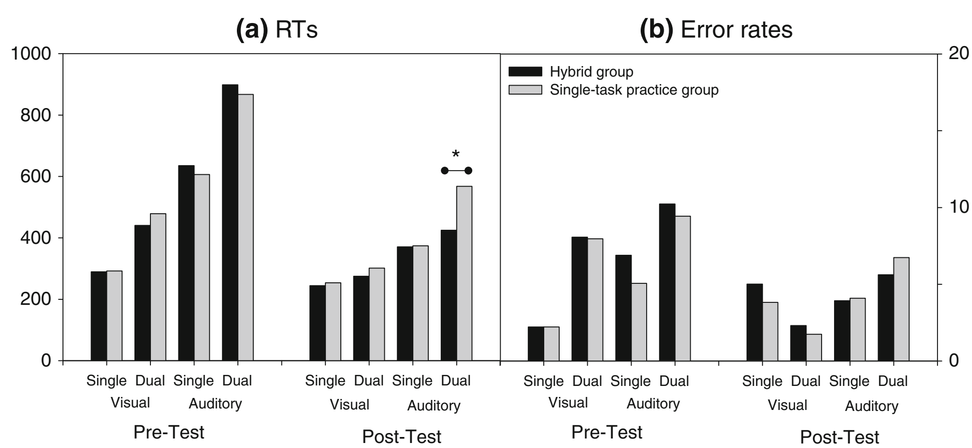

Fig. 2 Single-task and dual-task data in skill acquisition test during pre-test (first four blocks in Session 2) and post-test (Session 8) in the hybrid and single-task practice groups in Experiment 1. **a** RTs in ms, **b** error rates in percent. *Asterisks* represent significant differences. *Visual* visual task, *Auditory* auditory task, *Single* single-task trials, *Dual* dual-task trials

task trials ($M = 8.0\%$), $F(1, 16) = 9.553$, $p < .01$ (Fig. 2b). There was no effect of or interaction with GROUP.

Dual-task test for unspecific skills

In the dual-task test for unspecific skills, we compared the single-task and dual-task performance at the beginning of practice (i.e., pre-test) and after practice (i.e., post-test) in the hybrid and the single-task transfer groups. Importantly, the post-test performance was tested with the changed visual and auditory tasks in Session 9. Improved dual-task post-test performance in the hybrid group, compared to the single-task transfer group would point to a transfer of task coordination skills if it cannot be explained by different performance levels during pre-test. As for the pre-test of the skill acquisition test, we analyzed the single- and dual-task performance by comparing the RT and error data of the first two single-task blocks with that of the dual-task trials in the two following mixed blocks in Session 2.

The analysis of the *visual task* indicated no evidence for an effect of hybrid practice; this is indicated by a lacking effect of and interaction with GROUP, $Fs(1, 18) < 1$. Instead, we found increasing RTs from pre-test ($M = 353$ ms) to post-test ($M = 484$ ms), $F(1, 18) = 118.083$, $p < .001$, while RTs decreased from single-task trials ($M = 330$ ms) and to dual-task trials ($M = 507$ ms), $F(1, 18) = 134.208$, $p < .001$. The main effects of TESTPHASE and TRIALTYPE were qualified by the significant interaction of the two factors, $F(1, 18) = 10.173$, $p < .001$. As illustrated in Fig. 3a, dual-task RTs showed a larger increase compared with single-task RTs; so, dual-task costs of $M = 149$ ms during pre-test, $t(19) = 7.778$, $p < .001$, increased to $M = 205$ ms during post-test, $t(17) = 13.741$, $p < .001$, when the dual-task situation including the changed component tasks was presented.

The analysis of the error rates (Fig. 3b) showed higher error rates during post-test ($M = 9.2\%$) than during pre-test ($M = 5.4\%$), $F(1, 18) = 23.941$, $p < .001$, as well as higher error rates in dual-task trials ($M = 10.0\%$) than in single-task trials ($M = 4.5\%$), $F(1, 18) = 53.360$, $p < .001$. TESTPHASE and TRIALTYPE interacted significantly, $F(1, 18) = 8.417$, $p < .001$: Single-task error rates showed a larger increase from pre- to post-test when compared with error rates in dual tasks. So, dual-task costs of $M = 7.4\%$ during pre-test, $t(19) = 7.237$, $p < .001$, decreased to $M = 3.6\%$ during post-test, $t(19) = 3.669$, $p < .01$, across the two groups of participants. This significant reduction of the error costs indicates a speed–accuracy trade-off that might explain the increased costs in the RT data. Important for the question concerning the transfer of improved task coordination skills, the visual-task analysis provides no evidence for a transfer of these skills to the dual-task situation of Session 9 with changed visual and auditory tasks after eight practice sessions.

For the *auditory task*, RTs were larger in dual-task trials ($M = 899$ ms) compared with single-task trials ($M = 578$ ms), $F(1, 18) = 363.016$, $p < .001$ (Fig. 3a). The main effect of TRIALTYPE was qualified by an interaction between TESTPHASE and TRIALTYPE, $F(1, 18) = 86.935$, $p < .001$, demonstrating lower dual-task costs during pre-test ($M = 195$ ms), $t(19) = 9.250$, $p < .001$, than during post-test ($M = 449$ ms), $t(19) = 20.743$, $p < .001$. The three-way interaction of TESTPHASE, TRIALSTYPE, and GROUP was not significant, $F(1, 18) < 1$. Thus, the RT data in the auditory task do not support the assumption of a transfer of acquired task coordination skills to dual tasks with two changed tasks. On one side, this finding is consistent with the hypothesis of task-specific skills, while it is inconsistent with the hypothesis of task-unspecific skills.[2]

However, one the other hand based on the RT findings alone we cannot completely reject the hypothesis of task-unspecific skills. This is because the analysis of the error rates in the auditory task reveals a dual-task performance advantage of the hybrid group compared to the single-task transfer group. In particular, the analysis of error rates showed a three-way interaction of TESTPHASE, TRIALTYPE, and GROUP, $F(1, 18) = 4.698$, $p < .05$. This finding suggests that single-task and dual-task performance changed differently from pre-test to post-test in the two groups of participants. As illustrated in Fig. 3b, dual-task error rates in the hybrid group ($M = 8.4\%$) were lower than those error rates in the single-task transfer group ($M = 14.4\%$) during post-test, $t(18) = 2.636$, $p < .05$, while the single-task error rates of that tests were similar in both practice groups, $t(18) < 1$. The pre-test data revealed similar single-task and dual-task error rates in both groups of participants, $ts(18) < 1.012$, $ps > .33$; thus, dual-task performance during post-test benefited from hybrid practice and this benefit was not based on different initial performance levels in the single-task transfer and hybrid groups.

Interestingly, the dual-task test for unspecific skills demonstrates that the dual-task advantage of the hybrid

[2] Across both the hybrid and the single-task transfer groups, the reason for the increase in visual and auditory dual-task RT costs from pre- to post-test may be related to the particular way in which we changed the stimulus and the mapping information in both tasks during transfer. In fact, the change from a position mapping to a size mapping in the visual task and from a compatible to an incompatible mapping in the auditory task resulted in a reduced degree of compatibility between tasks' stimuli and responses (Kornblum, Hasbroucq, & Osman, 1990) that may impose increased cognitive demands on operations of task coordination (Ruthruff et al., 2006). This increase may result in additional performance costs mainly in dual-task situations and therefore may explain the observation of increased dual-task RT costs.

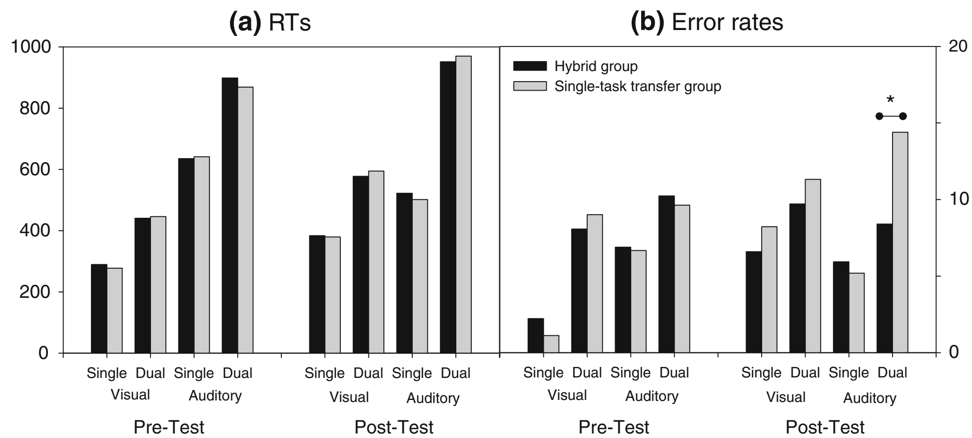

Fig. 3 Single-task and dual-task data in dual-task test for unspecific skills during pre-test (first four blocks in Session 2) and post-test (Session 9) in the hybrid and single-task transfer groups in Experiment 1. **a** RTs in ms, **b** error rates in percent. *Asterisks* represent significant differences. *Visual* visual task, *Auditory* auditory task, *Single* single-task trials, *Dual* dual-task trials

group compared with the single-task transfer group occurred in the error data of the auditory task, while there was no difference in the RT data. This differs from earlier findings in the present study (i.e., Experiment 1) and from findings in Liepelt et al. (2011), which revealed hybrid practice advantages in the RTs but not in the error rates. We believe that a shift of the group difference between the measurements of dual-task performance (i.e., from RTs to error rates) may point to the fact that participants differ in their strategy in dual-task processing during previous and the present test situations (Kantowitz, 1978; Lien, Proctor, & Allen, 2002; Shin, Cho, Lien, & Proctor, 2007). While we did not explicitly change instructions from practice to transfer (e.g., from speed instructions to accuracy instructions), it might be the case that participants of the hybrid group were used to respond with high accuracy and relaxed response speed when both individual tasks were changed. In contrast, participants may be prone to focus on the speed of responses and relaxed response accuracy in dual-task situations, when no or only one individual task was changed. Such a change may explain why the dual-task advantage in the hybrid group, compared to the single-task transfer group, was shifted from the RT measures to the error measures.

In sum, there is no dual-task performance advantage in the RT data after hybrid practice. On one hand, this would support the hypothesis of task-specific skills and not be consistent with the hypothesis of task-unspecific skills. Nevertheless, we cannot definitively exclude the acquisition of task-unspecific skills because of the observed error rate benefit of the hybrid group.

Experiment 2

The main purpose of this experiment was to investigate whether task coordination skills, acquired during dual-task practice, can be transferred to a task switching situation (Allport, Styles, & Hsieh, 1994; Monsell, 2003; Rogers & Monsell, 1995; see Kiesel et al., 2010, for a recent review). The investigation of such a transfer in the present *task switching test for unspecific skills* is plausible because the reduced dual-task errors after hybrid practice in the dual-task test for unspecific skills indicate that task coordination skills may at least partially be transferable to unpractised situations. Furthermore, Lien et al. (2003) as well as Sigman and Dehaene (2006) assumed the involvement of similar processes to control and to coordinate two tasks in dual-task and task switching situations with simultaneous and sequential task presentations, respectively. For example, these processes may be associated with the requirement to implement two different task sets in these situations.

In an exemplary task switching situation, participants perform a letter task (consonant vs. vowel) and a digit task (odd vs. even; Rogers & Monsell, 1995). The two tasks are presented in single-task and in mixed blocks. In single-task blocks, either the letter or the digit task is presented exclusively. Alternatively, mixing of the two tasks results in task switches or task repetitions from one trial to the next in mixed blocks. There are two types of performance costs that can be measured in this situation. First, *mixing costs* are defined as the difference between the impaired performance in mixed blocks and the performance in single-task blocks (e.g., Kray & Lindenberger, 2000; Mayr, 2001); they are associated with the demands to maintain and select two task-sets in working memory. Second, *switch costs* are defined as the difference between the impaired performance in task switch trials and the performance in task repetition trials within the mixed blocks (Rogers & Monsell, 1995). They are explained by processes of task-set activation of the following task, processes of task-set inhibition of the previous task, or a combination of both during switching (for a review see Monsell, 2003). If task coordination skills, acquired during dual-task practice, transfer to a task switching situation, we would expect a reduction of mixing and/or switch costs after hybrid practice contrasted with the results of single-task practice in the hybrid group and the single-task transfer group, respectively (see "Experiment 1"). This would be consistent with the hypothesis of task-unspecific skills. In contrast, the hypothesis of task-specific skills predicts no reduction of performance costs in the task switching situation after hybrid practice contrasted with the results of single-task practice.

However, we were also aware of the possibility that extended training may have unspecific effects on performance in subsequent transfer situations (Castel, Pratt, & Drummond, 2005). For example, unspecific learning may occur due to the repeated performance of cognitively demanding sensori-motor tasks, which may improve retrieval and implementation of task sets. Unspecific learning should not affect the coordination of two tasks but might optimize sensori-motor task performance per se. To control for possible unspecific learning effects, we included an additional control group in Experiment 2. This control group practiced neither single nor dual tasks before being tested in the task switching situation; we refer to this condition as the non-learner group.

Methods

Participants

The hybrid group and the single-task transfer group consisted of the same participants as in Experiment 1. The non-learner group included 14 participants (9 females) with a mean age of $M = 25.1$ years (SD $= 4.3$ years, age range from 18 to 32 years).

All participants had normal or corrected to normal vision and were not informed of the purpose of the experiment. They were paid for participation at a rate of 8 € per session plus performance-based bonuses.

Apparatus

The apparatus was identical to the one used in Experiment 1.

Stimuli and component tasks

A stimulus pair consisting of a letter and a digit was presented in each trial of the task switching paradigm. The letter was either a consonant (sampled randomly from the set G, K, M, and R) or a vowel (sampled randomly from the set A, E, I, and U). The digit was either even (sampled randomly from the set 2, 4, 6, and 8) or odd (sampled randomly from the set 3, 5, 7, and 9). Each character pair was displayed in Helvetia font, which subtended 1.1° horizontally and 0.8° vertically. Stimulus pairs were presented at the center of four boxes that defined the corners of a square subtending 5.5° horizontally and vertically when participants were seated 60 cm (approx. 24 inches) away from the computer screen. In the letter task, participants were instructed to press the left key with the left index finger when a consonant was presented and the right key with the right index finger when a vowel was presented in the stimulus pair. In the digit task, participants were instructed to press the left key with the left index finger when an even digit was presented and the right key with the right index finger when an odd digit was presented.

Design and procedure

In each trial, the stimulus pair remained on the screen until the participant pressed a key or 5,000 ms had elapsed. Then a blank interval of 150 ms followed before a new trial began when the participant had responded correctly. When the participant responded incorrectly, a beep sounded for 30 ms and the following inter-trial interval was extended to 1,500 ms.

Presentation of the first stimulus pair in each block started in the upper left box and the trial-to-trial presentation moved clockwise to the subsequent box. Two types of blocks were presented consisting of 48 trials each. In single-task blocks, either the letter task or the digit task was instructed. In mixed blocks, participants performed the letter task when the stimulus pairs were presented in the upper left or upper right boxes and they performed the digit task when the stimulus pairs were presented in the lower right or lower left boxes on the monitor. In this manner, trials with task switches were alternated with trials of task repetitions in mixed blocks. Participants were instructed to perform with speed and accuracy in each block.

In the pre-test sessions, the task switching test started with two single-task blocks including one letter task block and one digit task block. Half of the participants performed the letter task first and the digit task second; the remaining participants performed the two tasks in reversed order. Following the two single-task blocks, two mixed blocks were presented. In the post-test session, the identical block sequence from the pre-test phase was presented twice.

The pre- and post-tests were conducted before and after the practice sessions, respectively, in the hybrid and the single-task transfer groups. There was an identical time delay between both tests for the non-learner group. That is, we re-invited this group after the single-task transfer and hybrid groups had completed the dual-task transfer Session 9.

Results and discussion

In order to assess the possibility of transfer of task coordination skills to task switching situations we analyzed the

RT and error data of the hybrid, the single-task transfer, and of the non-learner groups during the task switching pre and post-test. Before analyzing participants' task switching performance, we excluded all trials from the RT analysis in which responses were incorrect or slower than 5,000 ms, and averaged the RTs for the letter and the digit tasks. The comparison of the mean performances in mixed blocks and single-task trials served as a measure of mixing costs; the comparison of the mean performances in switch and repetition trials in mixing blocks served as a measure of switch costs.

For *mixing costs*, RTs and error data were analyzed in separate mixed-measures ANOVAs with TESTPHASE (pre-test vs. post-test) and TRIALTYPE (mixed-block trials vs. single-task trials) as within-subject factors and GROUP (hybrid group, single-task transfer group, and non-learner group) as a between-subject factor. RTs were generally longer in mixed-block trials ($M = 1{,}093$ ms) than in single-task trials ($M = 642$ ms), $F(1, 31) = 265.393$, $p < .001$, as were RTs during pre-test ($M = 963$ ms) compared to RTs during post-test ($M = 773$ ms), $F(1, 31) = 81.918$, $p < .001$. This change from pre- to post-test was different in the single-task, hybrid, and non-learner groups, $F(2, 31) = 6.678$, $p < .01$, as well as in mixed-block and single-task trials, $F(1, 31) = 18.437$, $p < .001$. Most important for the question on transferable task coordination skills, these effects were qualified by a three-way interaction between TRIALTYPE, TESTPHASE, and GROUP, $F(2, 31) = 3.515$, $p < .05$. As illustrated in Fig. 4a, this interaction reflects a specific advantage in mixed-block trials of hybrid and single-task practice over the non-learner condition exclusively at post-test. In fact, RTs in mixed blocks were larger in the non-learner group ($M = 1{,}131$ ms) compared to those of the other two groups (hybrid practice group: $M = 895$ ms, single-task transfer group: $M = 859$ ms), both $ts(22) > 2.041$, both $ps < .01$. In contrast, post-test RTs in single-task trials were similar in all groups as were single and dual-task RTs at pre-test, $ts < 1$. These RT results demonstrate unspecific practice effects (Castel et al., 2005) because single-task practice and hybrid practice are equally efficient to reduce mixing costs in comparison to a control group that received no task practice at all. There is, however, no evidence for a transfer effect of task coordination skills and thus no evidence for the hypothesis of task-unspecific skills. The present findings are therefore consistent with the hypothesis of task-specific skills. The error analysis of mixing costs indicated higher error rates at pre-test ($M = 8.3\%$) than at post-test ($M = 5.7\%$), $F(1, 31) = 10.159$, $p < .01$, as well as higher error rates in mixed-block trials ($M = 9.4\%$) than in single-task trials ($M = 4.6\%$), $F(1, 31) = 27.380$, $p < .001$ (Table 3).

For the *switch costs*, RTs (Fig. 4b) and error data (Table 3) during pre- and post-test in the hybrid, single-task transfer, and non-learner group were analyzed in switch trials and repetition trials. These analyses showed no evidence for a transfer effect on switch costs after hybrid and/or single-task practice. In the RT data, this is indicated by a lacking three-way interaction of TRIALTYPE, TESTPHASE, and GROUP, $F(2, 31) = 1.843$, $p > 18$. Instead, we found larger RTs during pre-test ($M = 1{,}225$ ms) than during post-test ($M = 962$ ms), $F(1, 31) = 56.116$, $p < .001$, and larger RTs in switch trials ($M = 1{,}329$ ms) compared to repetition trials ($M = 858$ ms), $F(1, 31) = 161.808$, $p < .001$. RTs at post-test were generally larger in the non-learner group ($M = 1{,}130$ ms) than in the hybrid ($M = 895$ ms) and the single-task practice group ($M = 859$ ms; see RT analysis of *mixing costs*), while there was no difference between the three groups at pre-test, $F(2, 31) = 5.949$, $p < .01$. The error data revealed higher error rates before practice ($M = 11.0\%$) than after practice ($M = 7.7\%$), $F(1, 31) = 6.403$, $p < .05$, and higher error rates in switch trials ($M = 13.0\%$) than in repetition trials ($M = 5.7\%$), $F(1, 31) = 80.017$, $p < .001$ (Table 3).

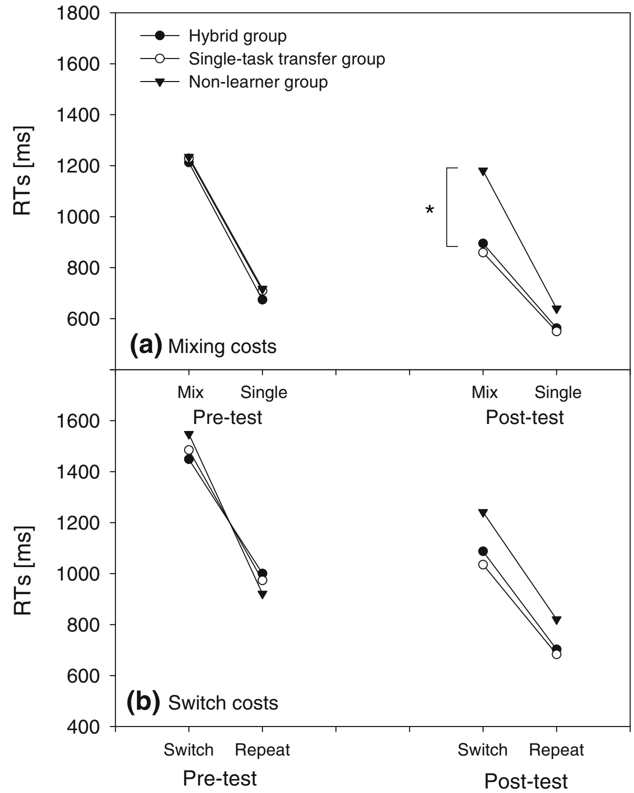

Fig. 4 RTs in task switching transfer test of Experiment 2. **a** Mixing costs: data of mixed blocks and single-task blocks in the hybrid practice, single-task transfer, and non-learner groups during pre- and post-test. **b** Switch costs: data of switch and repetition trials in the hybrid practice, single-task transfer, and non-learner groups during pre- and post-test. *Mix* mixed block trials, *Single* single-task trials, *Switch* switch trials, *Repeat* repetition trials

Table 3 Mean error rates in percent for the task switching test in Experiment 2 during pre-test and post-test sessions across single-task trials, mixed-blocks trials, repetition trials, and switch trials

	Sessions	
	Pre-test	Post-test
Hybrid group		
Single-task trials	7.5	4.0
Mixed-block trials	11.0	6.3
Repetition trials	6.3	5.8
Switch trials	15.8	10.5
Single-task transfer group		
Single-task trials	5.9	3.7
Mixed-block trials	11.1	8.1
Repetition trials	8.1	2.9
Switch trials	13.8	9.7
Non-learner group		
Single-task trials	3.4	3.1
Mixed-block trials	10.9	8.7
Repetition trials	6.4	4.8
Switch trials	15.4	12.6

General discussion

Several important findings were obtained about the improvement and the transferability of dual-task coordination skills in the present study. First, hybrid practice results in improved dual-task performance when compared with single-task practice effects in the dual-task transfer situation that was identical to the practice situation. This finding shows that improved skills are acquired during hybrid practice when compared with results of single-task practice. Furthermore, this finding is consistent with the hypothesis of task-specific skills: acquired task coordination skills are specific to the practiced tasks.

Second, when we changed the two component tasks in the dual-task transfer compared to the dual-task practice situation (i.e., dual-task test for unspecific skills), we observed no significant difference after hybrid compared to single-task practice when the dual-task performance was measured by RTs. This is consistent with the hypothesis of task-specific skills and provides no evidence for the hypothesis of task-unspecific skills. However, we cannot completely reject this latter hypothesis because dual-task transfer performance benefited from hybrid practice when measured by error rates; the error rate findings indicate that skills might at least partly be transferred from practice to transfer situations even if both component tasks are changed. Third, the present data showed no improved performance after hybrid practice compared to single-task practice in a situation of the task switching type (i.e., task switching test for unspecific skills). Thus, there is no evidence for the hypothesis of task-unspecific skills, while these findings are consistent with the hypothesis of task-specific skills. Fourth, the results of the hybrid and single-task practice groups showed unspecific practice effects with equally reduced mixing costs in the task switching situation when compared to the results in a control group that had no practice.

On the transferability of task coordination skills after hybrid practice

The present study specifies findings of Liepelt et al. (2011) that provided evidence in the RT data for transfer of task coordination skills to dual tasks with only one changed task. Improved task coordination skills may require constant characteristics between the practice and transfer situations, such as at least one non-changed component task, to show these effects. The present dual-task test for unspecific skills includes no such constant characteristics as both component tasks changed between practice and transfer.

Further, the exclusive error data benefit after hybrid practice in the changed dual-task situation is inconsistent with findings of former tests of transferability of improved task coordination skills. For instance, in studies of Kramer and colleagues (Kramer et al., 1995; Kramer, Larish, Weber, and Bardell, 1999) assumptions about the transferability of task coordination skills originate from a comparison of dual-task practice with fixed/equal priority between the component tasks (similar to the present task instruction) and dual-task practice with a variable priority schedule; the latter type of practice particularly showed improved dual-task RT performance in practice and transfer situations and thus provided evidence for the acquisition of improved task coordination skills. However, an exclusive comparison of conditions with fixed and variable priority may not be appropriate to focus on task coordination skills because it does not involve a comparison of conditions with and without dual-task practice. Unlike the conditions in the Kramer et al. studies the current investigation involved such a comparison, which is a fundamental corollary for testing task coordination skills associated with dual-task situations (Hirst et al., 1980; Kramer et al., 1995).

As regards the test of skill transfer to task switching (i.e., the task switching test for unspecific skills in Experiment 2), our data provided no evidence for transfer. This is surprising because previous studies provided evidence for skill transfer between structurally dissimilar task situations, including task switching situations. For example, Karbach and Kray (2009) provided evidence for transfer to dissimilar situations, e.g., Stroop or working memory tasks, after practice of task switching. Potentially, the transfer of task switching practice effects follows from the specific characteristics of this practice situation. In this situation, participants were instructed to perform two tasks and to follow a sequence with these tasks including task repetitions and task switches. These instructions of two tasks plus task sequence may be sufficiently demanding to enhance processes at the level that allows for transfers between structurally dissimilar task situations. In contrast, there was no such pre-instructed task sequence in the present study when two tasks were performed. The required task in the present practice situation was indicated by the presented task stimuli (i.e., visual and/or auditory stimuli). Therefore, no additional sequence information had to be maintained and coordinated in working memory during dual-task blocks. Thus, this situation may not include elements that enable transfers of task coordination skills to structurally dissimilar task situations, such as task switching.

A further reason why we found no transfer of task coordination skills to task switching may be that the present dual-task situation rather influences the coordination of visual and auditory stimulus processing. However, the applied task switching situation included two visual tasks. This may point to the fact that processes associated with the coordination of two visual tasks are not affected by skills coordinating visual-auditory task combinations that were practiced in the Schumacher et al. (2001) situation.

Additionally, the data of the task switching test for unspecific skills showed that both types of practice, i.e., single-task practice and hybrid practice result in transfer effects to the task switching situation. In detail, hybrid practice and single-task practice were equally efficient to reduce mixing costs in contrast to a control group with no practice. According to Kray and Lindenberger (2000), the equal reduction of mixing costs may indicate an equal improvement to maintain and select two tasks in the present task switching situation. Our findings suggest that the related skills may be acquired during both single-task and hybrid practice. This acquisition may result from the constant retrieval and implementation of two sensori-motor tasks in both types of practice (Castel et al., 2005).

An alternative explanation for the similarly reduced mixing costs after hybrid and single-task practice proposes that both types of practice may lead to an increased automatization of response selection processes; a reduced mental effort when maintaining the tasks in working memory may follow from this automatization. We assume, however, that automatization cannot explain the present mixing cost advantage after hybrid and single-task practice. This is so because stimulus–response transmission rules tremendously differ between practiced component tasks (i.e., location mapping in the visual task, pitch mapping in the auditory task) and the digit and letter task of the task switching situation. This difference between the visual task/auditory task (i.e., practice) and the digit task/letter task (i.e., transfer) and its stimulus–response transmission rules may not enable an increased automatization. This assumption is consistent with findings of Pashler and Baylis (1991) as well as Healy, Wohldmann, Sutton, and Bourne (2006) who showed no benefit of prior practice between two relatively similar versions of a symbol mapping or movement task, respectively.

Theoretical implications for accounts of dual-task practice

In the following, we discuss how the present findings of Experiment 1 might be integrated into accounts of practiced dual-task performance. The discussed accounts in this section explain practice-related improvement of dual-task performance by means of changed processing within the component tasks; note that this focus on component tasks provides mechanisms of practice-related improvement of dual-task performance in addition to task coordination skills. According to a *stage-shortening account*, dual-task performance is improved during practice because of shortened capacity-limited processes in these tasks (e.g., Dux et al., 2009; Pashler & Baylis, 1991; Ruthruff et al., 2006; Sangals et al., 2007; Van Selst et al., 1999). This account predicts that dual-task as well as single-task practice results in improved dual-task performance. The dual-task findings in Experiment 1 provide indications for this account. There was improved dual-task performance after both types of practice from pre- to post-test in the skill acquisition test (Fig. 2a). However, the larger amount of dual-task performance improvement after hybrid practice compared to single-task practice suggests that stage shortening is not conclusive to explain the entire improvement in the Schumacher et al. (2001) task situation.

A further account which may explain dual-task performance improvement with practice due to changes in the component tasks is the *automatization account*. According to this account, dual-task as well as single-task practice may completely automatize component-task processing and thus eliminate processes that compete for limited capacities in the cognitive system (e.g., Johnston & Delgado, 1993; Ruthruff et al., 2006). This elimination of capacity-limited processes should be associated with reduced interference between two tasks in dual-task situations and result in improved dual-task performance at the end of practice. The RT data of the dual-task test for unspecific skills are consistent with the assumption of the automatization account; these data showed similar effects of hybrid (including dual-task practice) and single-task practice. However, the automatization account cannot explain the present findings of smaller dual-task RT costs after hybrid practice compared with the effects of single-task practice in the skill acquisition test of the present study (Session 8) plus the findings of Experiments 1–3 in Liepelt et al. (2011); thus, the automatization account is not a plausible candidate to explain the observed dual-task practice effects.

According to the *integration account*, exclusively dual-task practice might produce an efficient integration of two tasks and combine them, in an extreme case, into a single super task (Hazeltine et al., 2002). Whereas two separate selection processes are performed at the beginning of practice, a single selection process of the combined task is processed after practice. The processing of two selection processes increases the likelihood of dual-task costs (e.g., due to sequential processing), while the likelihood is reduced with only one selection process. In contrast, single-task practice should not lead to an integration of both selection processes and therefore increases the likelihood of dual-task costs. Furthermore, this integrated selection of two responses after dual-task practice is related to the specific pairs of component tasks presented during practice (Hazeltine et al., 2002; Ruthruff et al., 2006).

The integration account is a plausible candidate to explain improved dual-task performance after hybrid practice compared with the performance after single-task practice when the identical component task is presented during practice and dual-task tests (as shown in Experiment 1 of the present and the study of Liepelt et al., 2011). However, Liepelt et al.'s findings in Experiments 2 and 3 showed improved dual-task performance in the hybrid group when solely the stimulus–response mappings of the visual or the auditory task were changed; this would not be consistent with the assumption that both tasks were integrated into one super-task representation, which leaves only one integrated response selection mechanism. In addition, the present study provided hints for a dual-task advantage after hybrid practice, which stem from the analysis of the error data in the present dual-task test for unspecific skills and which are not in line with the predictions of the integration account. Exactly this data pattern, however, is predicted by the assumption of improved task coordination skills (Hirst et al., 1980; Kramer et al., 1995). This assumption predicts, in particular, that the hybrid practice advantage is (at least partly) transferable to dual-task situations changed after practice and can thus explain the present and prior findings (Liepelt et al., 2011).

In sum, analyses of dual-task performance after hybrid and single-task practice in the practice and transfer situations are not consistent with predictions of the automatization and integration accounts. The present findings favor the assumption of improved task coordination skills to explain advanced dual-task performance after hybrid practice.

Possible limitations of the present study

Could it be that participants simply need more dual-task trials during hybrid practice to acquire transferable task coordination skills? Note that the present task paradigm includes more single-task than dual-task trials (i.e., single-task trials were included into single-task blocks and in 30 out of 48 trials in each dual-task block). In principle, there is no way to rule out this conjecture for any finite amount of practice given to participants; the possibility remains that more practice would eventually lead to transferable skills. However, participants in the hybrid group already performed more than 1,200 dual-task trials during eight practice sessions before we tested for transfer effects. We believe that a conclusion is warranted that under the current large amount of dual-task practice the current pattern of transfer effects are obtained. We believe that our findings are most valuable for the current research question of transfers of task coordination skills even under the current amount of practice. This is so because other studies either did not administer such a large amount of practice and/or did not apply a hybrid practice/single-task practice group design (e.g., Bherer et al., 2005; Kramer et al., 1995). Therefore, the findings of those studies are not as conclusive as those of our study with respect to the current research question.

Further, dual-task and single-task trials were intermixed within dual-task blocks of hybrid practice. This mix of trials does not allow us to draw inferences about the specific reasons of potential sources for the acquisition of task coordination skills. While single-task practice exclusively included single-task blocks, hybrid practice additionally includes dual-task blocks with intermixed single- and dual-task trials. Thus, dual-task blocks may differ from these single-task blocks in several aspects. For instance, dual-task blocks differ in the variability and predictability of trials types (i.e., single or dual tasks). Additionally, these blocks require the necessity to switch between component tasks. These differences make it hard to infer about the specific sources of acquired task coordination skills in hybrid compared to single-task practice. We stress at this point, however, that it could be the mix of different trial types and tasks within mixed blocks that lead to the acquisition of task coordination skills (Bherer et al., 2005; Kramer et al., 1995). Exclusive dual-task practice (Ruthruff et al., 2006) or single-task practice does not result in such skill acquisition (Liepelt et al., 2011; the present Experiment 1). A methodological investigation of the specific reasons of potential sources for this acquisition in mixed blocks (i.e., different trial types and/or tasks) is a promising question for the future studies, but is beyond the scope of the present work.

Summary

The present study provided evidence for the assumption of task-specific coordination skills, acquired during hybrid but not during single-task practice. Furthermore, based on error data in the novel dual-task situation, these skills are at least partly transferable. However, there is no evidence for such a transfer in the RT data of this novel dual-task situation and in the task switching situation. Instead, mixing two tasks during task switching benefits from hybrid and single-task practice.

Acknowledgments This research was supported by a grant of the German Research Foundation to T.S. (last author) and to P.F. as well as by a grant of CoTeSys (No. 439) to T.S. (last author). It is part of the dissertation of T.S. (first author) supervised by T.S. (last author). Thanks to Harold Pashler and Thomas Kleinsorge for their helpful comments on an earlier draft of this article. Correspondence concerning this article should be addressed to Tilo Strobach, Ludwig-Maximilians-University Munich, Department Psychology, Leopoldstr. 13, 80802 Munich, Germany. Electronic mail may be sent to tilo.strobach@psy.lmu.de.

References

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Conscious and nonconscious information processing: attention and performance XV* (pp. 421–452). Cambridge: MIT 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.

Beringer, J. (2000). Experimental runtime system. BeriSoft Cooperation, Frankfurtam Main (1987–2000).

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.

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.

Dux, P. E., Tombu, M. N., Harrison, S., Rogers, B. P., 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.

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.

Healy, A. F., Wohldmann, E. L., Sutton, E. M., & Bourne, L. E., Jr. (2006). Specificity effects in training and transfer of speeded responses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 534–546.

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 DC.

Kamienkowski, J. E., Pashler, H., Sigman, M., & Dehaene, S. (2011). Effects of practice on task architecture: Combined evidence from interference experiments and random-walk models of decision making. *Cognition, 119*, 81–95.

Kantowitz, B. H. (1978). Response conflict theory, error rates and hybrid processing: a reply to McLeod. *Acta Psychologica, 42*(5), 397–403.

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task switching training. *Developmental Science, 12*(6), 978–990.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Phillip, A., et al. (2010). Control and interference in task switching—a review. *Psychological Bulletin, 136*, 849–874.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychological Review, 97*(2), 253–270.

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 (Eds.), *Attention and performance XVII: cognitive regulation of performance: Interaction of theory and application* (pp. 617–652). Cambridge: The MIT Press.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*, 126–147.

Lien, M.-C., Proctor, R. W., & Allen, P. A. (2002). Ideomotor compatibility in the psychological refractory period effect: 29 years of oversimplification. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 396–409.

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., Strobach, T., Frensch, P., & Schubert, T. (2011). Improved inter-task coordination skills after extensive dual-task practice. *Quarterly Journal of Experimental Psychology, 64*(7), 1251–1272.

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., Laguẽ-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.

Mayr, U. (2001). Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging, 16*, 96–109.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134–140.

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.

Oberauer, K., & Kliegl, R. (2004). Simultaneous cognitive operations in working memory after dual-task practice. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 689–707.

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

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.

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.

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.

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

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.

Shin, Y.-K., Cho, Y.-S., Lien, M.-C., & Proctor, R. W. (2007). Is the psychological refractory period effect for ideomotor compatible tasks eliminated by speed-emphasis instructions? *Psychological Research, 71*, 553–567.

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

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

Strobach, T., Frensch, P. A., & Schubert, T. (2008). The temporal stability of skilled dual-task performance. In: Zimmer, H. D., Frings, C., Mecklinger, A., Opitz, B., Pospeschill, M. & Wentura, D. (Eds.), Cognitive Science 2007. Saarbrücken: Proceedings of the 8th Annual Conference of the Cognitive Science Society of Germany.

Strobach, T., Liepelt, R., Schubert, T., & Kiesel, A. (in press). Task switching: effects of practice on switch and mixing costs. *Psychological Research*.

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.

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

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