

# Improved intertask coordination after extensive dual-task practice

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This study examines whether an improved intertask coordination skill is acquired during extensive dual-task training and whether it can be transferred to a new dual-task situation. Participants practised a visual–manual task and an auditory–vocal task. These tasks were trained in two groups matched in dual-task performance measures before practice: a single-task practice group and a hybrid practice group (including single-task and dual-task practice). After practice, the single-task practice group was transferred to the same dual-task situation as that for the hybrid practice group (Experiment 1), both groups were transferred to a dual-task situation with a new visual task (Experiment 2), and both groups were transferred to a dual-task situation with a new auditory task matched in task difficulty (Experiment 3). The results show a dual-task performance advantage in the hybrid practice group over the single-task practice group in the practised dual-task situation (Experiment 1), the manipulated visual-task situation (Experiment 2), and the manipulated auditory-task situation (Experiment 3). In all experiments, the dual-task performance advantage was consistently found for the auditory task only. These findings suggest that extended dual-task practice improves the skill to coordinate two tasks, which may be defined as an accelerated switching operation between both tasks. This skill is relatively robust against changes of the component visual and auditory tasks. We discuss how the finding of task coordination could be integrated in present models of dual-task research.

**Keywords:** Dual task; Practice; Learning; Intertask coordination.

Cognitive capacity is often overloaded when we perform two tasks simultaneously. We can all remember our miserable performance during our

first driving lessons where we felt swamped by the different activities that had to be coordinated simultaneously (e.g., Levy, Pashler, & Boer,

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2006). However, after extended practice, most people are capable of performing different activities at the same time fairly well. That is, they show improved performance in situations of simultaneous task processing after practice. So far it is unclear, however, whether improved dual-task performance is mediated by an improved task-coordination skill that may be acquired during dual-task practice. In the present study, we investigated whether dual-task practice leads to an improved skill to coordinate two tasks, which may provide a new way of understanding how people cope with basic processing limitations of the cognitive system.

Simultaneous performance of two choice reaction-time tasks leads to dramatic dual-task costs, which are typically measured by a difference in reaction times (RTs) and error rates between dual-task and single-task situations (e.g., Pashler, 1994; Telford, 1931; Welford, 1952). Dual-task costs are often explained by a processing limitation present in the cognitive system. Prominent models of dual-task research differ with respect to the exact information-processing stage where this limitation is placed within the task-processing stream and whether this limitation is structural or strategic in nature. A prominent and widely accepted model developed to explain dual-task costs is the so-called *response selection bottleneck* (RSB) model (Pashler, 1994; Pashler & Johnston, 1998; Welford, 1952). According to the RSB model, peripheral stages in the component tasks (perception and motor execution) that constitute a dual-task situation can be processed with any other stage in parallel while the central *response selection* (RS) stage can only be processed in one task at a time. This leads to serial processing of the RS stages when two tasks have to be performed at the same time. When Task 1 occupies this bottleneck, the corresponding stage of Task 2 cannot be executed and needs to be postponed until Task 1 has left the bottleneck. For the time of the postponement of Task 2 processing, dual-task costs emerge. According to the authors, the RSB is a structural, immutable capacity limitation inherent in the cognitive system. The existence of dual-task costs can

alternatively be explained with the central capacity-sharing model (Tombu & Jolicoeur, 2003). As in the RSB model, the capacity limitation is placed at the central stage. Different to the RSB model, the central capacity limitation does not work in an all-or-none fashion, but capacity is shared between both tasks so that multiple stimuli can simultaneously be processed. The RSB model can be viewed as a special case of the capacity-sharing model, in which the processing capacity is designated as 100% to Task 1 and as 0% to Task 2. Alternatively one can describe the central capacity-sharing model as a bottleneck model in which bottleneck processing can rapidly switch between tasks without costs. Meyer and Kieras (1997a, 1997b) developed an adaptive executive control model derived from the EPIC (executive processing–interactive control) architecture to account for dual-task costs. This architecture assumes that according to specific task demands, central stages of two component tasks can proceed either sequentially or in parallel. Dual-task costs emerge, when strategic bottlenecks are introduced. According to the model, bottlenecks can theoretically be introduced at any stage, such as perception, central, or motor stages.

Despite the numerous findings of considerable performance costs in dual-task situations, a number of recent studies suggest that dual-task processing can be optimized as a result of extensive practice. This optimization is indicated by an extreme (sometimes complete) reduction of dual-task costs after several hours of practice. Practice-related reductions in dual-task costs were shown in dual-task situations using easy choice reaction time tasks (e.g., Hazeltine, Teague, & Ivry, 2002; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006; Schumacher et al., 2001; Van Selst, Ruthruff, & Johnston, 1999), more complex continuous tasks (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Spelke, Hirst, & Neisser, 1976), memory retrieval tasks (Nino & Rickard, 2003), or even complex memory updating tasks (Göthe, Oberauer, & Kliegl, 2007; Oberauer & Kliegl, 2004).

Participants in a study by Schumacher et al. (2001), for example, had to perform a dual-task situation consisting of a visual–manual (VM) and an auditory–vocal (AV) choice reaction task. Both tasks were presented in single-task and dual-task situations. In single-task situations, either VM or AV stimuli were presented separately during an entire block. In dual-task situations, a VM and an AV stimulus were presented simultaneously (i.e., using a stimulus onset asynchrony, SOA, of zero ms), and the task instructions emphasized equal priority to both tasks. Importantly, Schumacher et al. (2001) reported that after five practice sessions the RTs for the VM and the AV task did not differ between single-task and dual-task conditions, showing evidence for perfect time-sharing by the end of training.

Several studies have aimed to understand the processing changes that occur within each component task during single-task and dual-task practice (Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Pashler & Baylis, 1991; Ruthruff et al., 2001, 2003, 2006; Sangals, Wilwer, & Sommer, 2007; Schumacher et al., 1999). However, little is known about learning mechanisms that improve intertask coordination (ITC) due to dual-task practice and about its possible contribution to the practice-related reduction of dual-task costs (Bherer et al., 2005, 2008; Hirst et al., 1980; Kramer, Larish, & Strayer, 1995). It is theorized that such an ITC skill might be associated with improved control and coordination of the processing streams capable of integrating both component tasks of a dual-task situation (Hazeltine et al., 2002). For instance, this skill might improve a switching operation between the processing streams of two tasks in dual-task situations (Band & van Nes, 2006; Lien, Schweickert, & Proctor, 2003). According to several authors, such an ITC skill should only be acquired and optimized under extensive dual-task practice conditions but not under single-task practice (Bherer et al., 2005, 2008; Hirst et al., 1980; Kramer et al., 1995; Maquestiaux, Hartley, & Bertsch, 2004; Spelke et al., 1976). A second important characteristic of the acquired ITC skill

is that such a skill should at least be partially independent of the specific properties of the component tasks presented during dual-task practice (Hirst et al., 1980; Kramer et al., 1995). Accordingly, the ITC skill should be transferable across different dual-task situations.

To test the transfer assumption, Kramer et al. (1995) compared dual-task performance of participants in an old practised dual-task situation and in a new dual-task transfer situation after hybrid practice combining single-task and dual-task training. The authors reported evidence for improved coordination in the transfer situation, especially for situations when participants were not instructed to respond with a fixed task priority. While single-task training can lead merely to automaticity of the given stimulus–response mappings, dual-task training can lead to the acquisition of coordination strategies required in a dual-task situation. On the other hand, while task coordination cannot be acquired by pure single-task training, dual-task training may slow down or prevent learning of the individual tasks. To combine the relative strengths and weaknesses of these two training situations, the authors proposed hybrid practice to be most efficient to promote transfer of a skill needed in dual-task processing. However, the Kramer et al. study did not include a single-task practice control group to test whether the skill acquired is really dual-task specific. Exactly this, however, was aimed for in a more recent study conducted by Ruthruff et al. (2006). They investigated effects of single-task and dual-task practice using a psychological refractory period (PRP) paradigm (e.g., Pashler, 1994; Schubert, 1999). In this type of dual-task situation, two component tasks were presented in close succession with various time intervals between the onsets of a first and a second task. Participants were given fixed-priority instructions on the first task. In Experiment 1 of the Ruthruff et al. (2006) study, one of the groups practised an AV and a VM choice reaction task in dual-task situations of the PRP type for eight sessions (Group 1). A further group exclusively practised the AV task under single-task practice conditions (Group 2). In the following transfer

sessions, both groups performed the AV and the VM task in dual-task situations. The results showed similar dual-task performance in the dual-task learning Group 1, and in Group 2, which practised only the AV task. In contrast to previous findings (Bherer et al., 2005, 2006; Kramer et al., 1995), this finding is in line with the assumption that dual-task practice improves dual-task performance, not by improving ITC skills, but simply by improving the processing of the single component task processes. However, a number of reasons may have prevented the acquisition of ITC skills in the study of Ruthruff et al. (2006). First, the authors applied no hybrid training strategy combining dual-task and single-task practice, as proposed by Bherer et al. (2005, 2006) and Kramer et al. (1995), the latter thought to be more appropriate for the acquisition of an ITC skill. Additionally, in a dual-task situation of the PRP type, like that in Ruthruff et al. (2006), the task instructions continuously prioritize the execution of the same task (the first task), throughout the experiment. The execution of the second task, however, should always succeed the execution of the first task. Accordingly, such a fixed order instruction of response execution in PRP-like paradigms may not be optimal for the development of an ITC skill, as it does not foster concurrent task performance (Bherer et al., 2005, 2008).

Based on the studies mentioned so far, it remains an open question whether dual-task practice is more than the sum of single-task practice when applying a hybrid training strategy in combination with an equal priority instruction. The aim of the present study was, therefore, to test whether ITC can be acquired during prolonged hybrid practice. This was done by comparing dual-task performance of a hybrid practice group with a group that practised the same tasks under single-task practice conditions. To provide optimal conditions for dual-task cost reduction and the acquisition of ITC, we used hybrid training by applying the Schumacher et al. (2001) paradigm and the related training regime in that study. Additionally, the Schumacher et al. paradigm has proven to lead to a strong decrease of dual-task

costs within a manageable timescale. Further, we tested the second characteristic proposed for ITC (i.e., transferability) by transferring both the hybrid practice and the single-task groups to new dual-task transfer situations and comparing their performance in these situations after practice. The findings will bring a theoretical advance for the type of practice that is optimal for the acquisition of ITC. Further, it may show up ways how ITC can be integrated into present models of dual-task research enabling dual-task cost reduction.

### The present study

In Experiment 1, we tested for the acquisition of ITC during dual-task practice by comparing the dual-task performance (dual-task costs and dual-task RTs) of two groups (hybrid practice group and single-task group) in a final dual-task transfer session after the same amount of practice. If dual-task training leads to an acquisition of ITC, then a dual-task performance advantage should occur for the hybrid practice group, as compared to the single-task group after practice. In contrast, if ITC is not acquired but automatization of the single tasks explains the complete practice-related reduction of dual-task costs (Ruthruff et al., 2006), then we should find similar dual-task performance in the hybrid practice and the single-task group during transfer. The number of stimulus contacts with the visual and auditory stimuli given during practice was identical for both groups in order to provide an equal amount of practice and an equal level of processing automatization in the component tasks (Kramer et al., 1995).

In Experiments 2 and 3, we tested the transferability of ITC to other task situations. In order to test the independence of ITC from the stimulus and mapping characteristics of the component tasks given during training, we compared dual-task performance between a hybrid and a single-task learning group in two different dual-task transfer situations. In these situations, we manipulated the stimuli and the stimulus–response mapping of the VM task (Experiment 2) and the stimulus–response mapping of the AV task

(Experiment 3). The rationale of these manipulations was the following. If ITC, which is, theoretically, acquired during dual-task practice, is independent of the specific task characteristics (Schmidt & Bjork, 1992) present during practice, then it should be applicable even in a transfer situation with changed component tasks; this change should not lead to a disappearance of the dual-task practice advantage in the hybrid group over the single-task group. If, however, participants acquire a specific ITC skill during dual-task practice that is tied to the characteristics either of the visual or of the auditory task, then this skill should not be applicable in a transfer situation in which the particular task (visual or auditory) was changed. The ratios of the specific manipulations of the component tasks in Experiments 2 and 3 are explained later.

## EXPERIMENT 1

Dual-task performance of a hybrid practice group and a single-task group was compared after seven sessions of practice in a final transfer session (Session 8) in which both groups had to perform the same dual task that the hybrid practice group used during practice.

### Method

#### *Participants*

The 16 participants were all undergraduate students from the Humboldt-University, Berlin. The hybrid practice group consisted of 8 students (7 female, age 21–30 years, mean age: 23.5) while 8 age-balanced students (4 female, age 18–31 years, mean age: 25.2) were used as the single-task group. All participants were right-handed, had normal or corrected-to-normal vision, and were naive with regard to the hypotheses of the experiment. All participants gave their written informed consent to participate in the study, which was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

#### *Apparatus and stimuli*

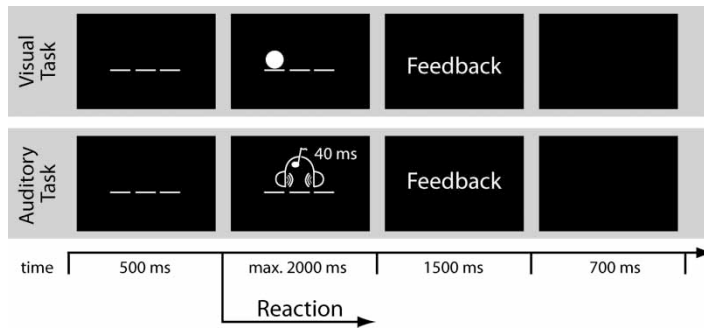
Stimuli were presented on a 17-inch colour monitor that was connected to a Pentium 1 PC. Experiments were carried out using ERTS (Experimental Runtime System) software (Beringer, 2000).

A VM and an AV task were performed. In the VM task, a circle appeared in one of three possible locations on the screen (left, middle, or right). Participants responded manually, indicating the location of the circle with the corresponding index, middle, or ring finger of the right hand (see Figure 1). The circles were white and were horizontally arranged on a black background on the computer screen. Each circle subtended approximately 2.5 cm, which corresponds to 2.38° of visual angle from a viewing distance of 60 cm. Three horizontal white lines served as placeholders at the possible left, middle, and right locations of the screen. The distance between the circles was 1 cm, which corresponded to approximately 0.95°. All circles subtended approximately 8.99°. Responses were recorded with a response board connected to the computer.

For the AV task, participants responded verbally to one of three possible sine-wave tones played on headphones by saying “ONE” to the low-frequency tone, “TWO” to the middle-frequency tone, or “THREE” to the high-frequency tone (German: “EINS”, “ZWEI”, and “DREI”; see Figure 1). The tones were 350 Hz, 900 Hz, or 1650 Hz in frequency. Verbal reactions were recorded with a Sony microphone connected to a voice key.

#### *Procedure and design*

A trial started with three white lines serving as placeholders signalling the beginning of a trial for 500 ms. After this period had elapsed, additionally a circle appeared in the VM task and remained visible until the participant responded or until a maximum of 2,000 ms had elapsed. Instead of the circle, a tone lasting for 40 ms was played in the AV task. RTs were given as feedback after each trial for 1,500 ms followed by a blank screen for 700 ms (see Figure 1). In dual-task trials, only the faster of the two RTs was given as



**Figure 1.** Stimulus sequence for each trial, as used in all experiments, shown for the visual task (upper panel) and the auditory task (lower panel). Both trials started with a warning signal (500 ms) showing three lines, which served as placeholders. Subsequently, a circle (imperative response stimulus for the visual task) appeared on top of these lines in the visual task and remained visible until the participant responded or until a maximum of 2,000 ms had expired. Also the auditory task started with a warning signal (500 ms) showing three lines. Subsequently, a tone was played for 40 ms (imperative response stimulus for the auditory task). The white lines remained visible until the participant responded or until a maximum of 2,000 ms had expired. Reaction times were given as feedback after each trial for 1,500 ms followed by a blank screen for 700 ms, which remained until the next trial started.

feedback at the end of the trial to minimize the load. When participants committed an error or 2,000 ms had elapsed, the RT feedback was replaced by the German word for error (“Fehler”) for the same amount of time.

*Hybrid practice group.* The procedure in the hybrid practice group was adapted from Schumacher et al. (2001). There were two types of blocks: single-task blocks and mixed blocks. In the single-task blocks, participants performed either 45 single-task trials of the VM task or 45 trials of the AV task. During mixed blocks, participants performed a mixture of 30 single-task trials (OR trials)—15 of the VM task and 15 of the AV task—and 18 dual-task trials. In dual-task trials, both tasks were presented simultaneously with zero SOA. All trials were intermixed randomly, thus requiring participants to switch between the processing of different single-task and dual-task trials. Participants were instructed to respond to both stimuli as quickly and accurately as possible during all blocks, to fully concentrate and to give equal priority to both tasks (for effects of time pressure on information processing see Sangals, Roß, & Sommer, 2004). Response order was free.

In Session 1, participants performed six VM and six AV single-task blocks that were presented in an alternating order. Half of the participants

started with a VM single-task block and the other half with an AV single-task block. Session 2 included six single-task blocks (3 VM and 3 AV) and eight mixed blocks. After two initial single-task blocks (1 VM and 1 AV single-task block), sequences of two mixed blocks and one single-task block followed. The order of blocks (first VM or AV task block) was counterbalanced across participants. The design in Sessions 3 to 8 was identical to that in Session 2 but these sessions included two additional mixed blocks at the end.

Reward was given in the form of a monetary performance-based pay-off to maximize participants’ motivation for achieving accurate and fast performance (see also Schumacher et al., 2001; Tombu & Jolicoeur, 2004). The pay-off 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 ms to 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 ms to 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. To increase motivation and task performance, the experimenter additionally encouraged participants verbally between blocks to respond as fast and accurately as possible.

*Single-task group.* Instructions and financial rewards were identical to those for the dual-task learning group. The single-task group received single-task blocks during practice (Sessions 1–7). To keep the number of stimulus contacts between dual-task and single-task conditions constant, 1 dual-task trial was replaced by 1 single-task trial of each task. 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 that for the hybrid practice group. Session 2 included 12 single-task blocks (6 VM and 6 AV) and 2 mixed blocks; these mixed blocks were included to analyze initial dual-task performance in the single-task learning group at the beginning of practice and to match this performance between practice groups. In Session 2, these 2 initial mixed blocks were introduced after 2 short single-task blocks. Then sequences of 1 short and 2 long single-task blocks followed. In Sessions 3 to 7, we presented 16 single-task blocks (8 VM and 8 AV single-task blocks). After 2 initial short single-task blocks, sequences of 2 long single-task blocks and 1 short single-task block followed. In Sessions 2 to 7, blocks with the VM and AV task

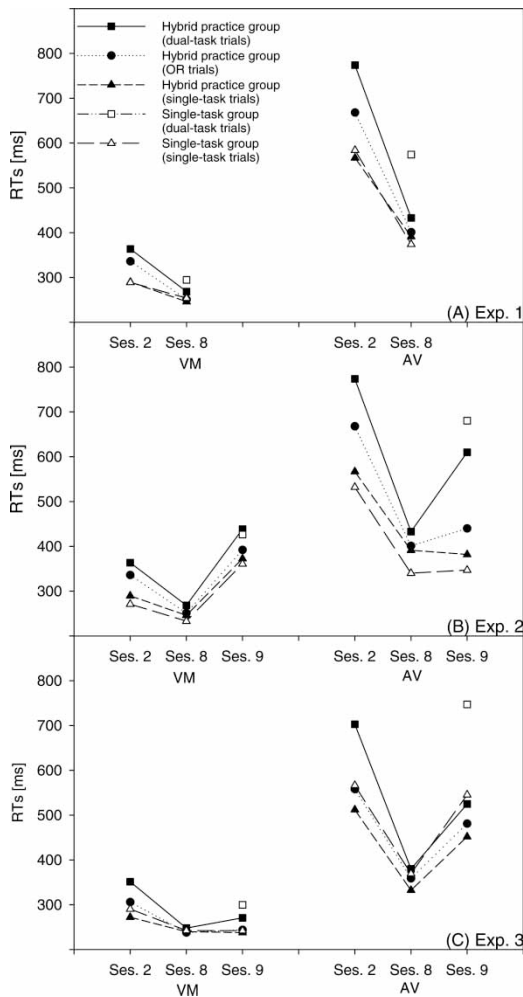
were alternated, and the first type of block (either VM or AV task) was counterbalanced between subjects. Session 8 was identical to the procedure in the dual-task learning group.

## Results

The results of all experiments are structured in the following way: We start by reporting dual-task practice effects for RTs and error rates of the hybrid practice group in Session 2 and Session 8. Then we report the single-task practice performance of the single-task group. To test for the acquisition of ITC, we compared the dual-task performance after practice between the hybrid practice group and the single-task group. Dual-task trials with two types of orders might obscure differences in dual-task performance (Nino & Rickard, 2003). Therefore, analyses of all group comparisons were limited to dual-task trials with the single response order (VM–AV), as previous studies using a similar dual-task design demonstrated that the VM task is the faster, and the AV task is the slower task in most of the trials (Hazeltine et al., 2002; Schumacher et al., 2001; Strobach, Frensch, & Schubert, 2008). Dual-task trials with a reversed response order (i.e., AV–VM) were excluded (3.3%). Prior to statistical RT analyses, we also excluded all trials in which responses were incorrect (4.4%). In order to use a strong and reliable criterion for dual-task costs, we compared RTs (see Figure 2) and error rates (see Table 1) in dual-task trials with those in single-task trials (in single-task blocks), as well as with those in single-task trials from the mixed blocks (OR trials). The first session was considered as practice and was excluded from further analyses. The same procedure was used in all experiments.

### *Hybrid practice group: Practice performance*

The practice data of the hybrid practice group in all experiments were analyzed with a repeated measures analyses of variance (ANOVA) including *session* (Session 2 vs. Session 8) and *trial type* (single-task trials, OR trials, and dual-task trials) as within-subject factors (see Figure 2). In this



**Figure 2.** Mean reaction times (RTs) in milliseconds (ms) in single-task trials in single-task blocks, single-task trials in mixed blocks (OR trials), and dual-task trials for the VM (visual-manual task) and AV (auditory-verbal task) for the hybrid practice group and the single-task group. The data are illustrated for the start of practice (Session 2), the end of practice (Session 8), and the transfer session (Experiment 1: Session 8; Experiments 2 and 3: Session 9). (A) Data of Experiment 1. (B) Data of Experiment 2. (C) Data of Experiment 3.

type of analysis, we focus on the interaction of both factors as they exclusively provide information about practice-related changes of dual-task performance. As illustrated in Figure 2, there was a significant Session  $\times$  Trial Type RT interaction in the VM task,  $F(2, 14) = 15.29$ ,  $p < .001$ ,  $\eta^2 =$

.79, indicating that dual-task costs (dual-task RTs minus single-task RTs) decreased from Session 2 ( $M = 74$  ms),  $t(7) = 6.64$ ,  $p < .001$ , to Session 8 ( $M = 22$  ms),  $t(7) = 3.30$ ,  $p < .05$ . Similarly, we found a reduced difference between dual-task trials and OR trials from the beginning (Session 2:  $M = 27$  ms),  $t(7) = 3.13$ ,  $p < .05$ , to the end of practice (Session 8:  $M = 17$  ms),  $t(7) = 5.26$ ,  $p < .001$ .

An identical analysis of the error rates demonstrated an interaction of Session  $\times$  Trial Type in the VM task,  $F(2, 14) = 12.53$ ,  $p < .01$ ,  $\eta^2 = .64$ . As can be seen in Table 1, dual-task costs for errors were not significant in Session 2,  $t(7) = 2.03$ ,  $p > .05$ , and single-task trials showed higher error rates than dual-task trials in Session 8 ( $M = 4.1\%$ ),  $t(7) = 4.28$ ,  $p < .01$ . There was no difference between the error rates of dual-task trials and those of OR trials in Session 2,  $t(7) = 2.24$ ,  $p > .05$ , nor in Session 8,  $t(7) < .01$ .

In the AV task, we also found a significant interaction of Session  $\times$  Trial Type,  $F(2, 14) = 19.69$ ,  $p < .001$ ,  $\eta^2 = .81$ . Dual-task costs ( $M = 207$  ms),  $t(7) = 6.82$ ,  $p < .001$ , and the difference between RTs in dual-task trials and OR trials ( $M = 106$  ms),  $t(7) = 5.10$ ,  $p < .001$ , in Session 2 were reduced—but still remained significant—in Session 8: dual-task costs,  $M = 42$  ms,  $t(7) = 3.20$ ,  $p < .05$ ; dual-task RTs vs. OR-trial RTs,  $M = 32$  ms,  $t(7) = 3.03$ ,  $p < .05$ . The identical error analysis of the AV task showed no interaction.

### Single-task group: Practice performance

Single-task practice data of the single-task group in the present experiment as well as in the following experiments were analyzed with a repeated measure ANOVA including the within-subject factor *session* (Session 2 vs. Session 8). As illustrated in Figure 2, this analysis showed a reduction of RTs in both the VM task,  $F(1, 7) = 33.27$ ,  $p < .001$ ,  $\eta^2 = .83$ , and the AV task,  $F(1, 7) = 66.80$ ,  $p < .001$ ,  $\eta^2 = .91$  over practice. The identical analysis of the error data in the VM task indicated an increase of the error rates with practice,  $F(1, 7) = 8.25$ ,  $p < .05$ ,  $\eta^2 = .54$ . The error analysis in the AV task showed no practice effect.



Table 1. Mean percentage error for the visual–manual and the auditory–verbal tasks at the beginning of practice, the end of practice, and the transfer session, in single-task trials in single-task blocks, single-task trials in mixed blocks, and dual-task trials for the hybrid practice group and the single-task group

Group			Experiment 1		Experiment 2			Experiment 3		
			Practice start (Session 2)	Transfer (Session 8)	Practice start (Session 2)	Practice end (Session 8)	Transfer (Session 9)	Practice start (Session 2)	Practice end (Session 8)	Transfer (Session 9)
Hybrid practice	VM	Single task	2.5	5.7	2.5	5.7	11.0	2.4	5.2	4.7
		OR	0.7	2.6	0.7	2.6	12.0	1.1	2.7	0.8
		Dual task	4.8	2.9	4.8	2.9	9.9	5.0	3.8	2.9
	AV	Single task	5.2	6.4	5.2	6.4	5.2	5.3	6.8	10.9
		OR	5.0	6.1	5.0	6.1	5.3	9.1	9.5	13.7
		Dual task	9.6	7.7	9.6	7.7	12.4	10.8	7.0	13.8
Single-task	VM	Single task	1.6	3.8	2.6	7.6	14.2	1.4	5.3	4.6
		OR		0.7			13.4			1.6
		Dual task		0.8			14.1			1.0
	AV	Single task	2.5	4.7	3.9	7.7	9.0	5.5	4.7	7.5
		OR		3.9			7.5			12.3
		Dual task		6.8			13.6			14.0

Note: VM = visual–manual task. AV = auditory–verbal tasks. Beginning of practice: Session 2. End of practice: Session 8. Transfer session—Experiment 1: Session 8; Experiment 2: Session 9; Experiment 3: Session 9. Single task: single-task trials in single-task blocks. OR: single-task trials in mixed blocks. Dual task: dual-task trials.

### Single-task group versus hybrid practice group: Testing for ITC

*VM task.* To test for the acquisition of ITC, we performed a mixed measure ANOVA with the between-subject factor *group* (hybrid practice group vs. single-task group) and the within-subject factor *trial type* (single tasks vs. dual tasks) on the data of Session 8 (Figures 2 and 3). The ANOVA on the RT data indicated that the difference between the performance levels of the hybrid and the single-task group was not significant,  $F(1, 14) = 3.71, p > .05, \eta^2 = .21$ . There was also no significant interaction of Group  $\times$  Trial Type,  $F(1, 14) = 3.07, p > .05, \eta^2 = .28$ . A main effect of trial type indicated different performance in single-task and dual-task trials across both groups of participants,  $F(1, 14) = 36.41, p < .001, \eta^2 = .75$ . The data showed that participants in both groups responded slower in dual tasks ( $M = 281$  ms) than in single tasks ( $M = 249$  ms), reflecting significant dual-task costs in Session 8.

An identical analysis on error rates showed no significant difference between both groups,  $F(1, 14) = 3.89, p > .05, \eta^2 = .19$ , and no significant interaction of Group  $\times$  Trial Type,  $F(1, 14) < 1$ . However, a main effect of trial type was

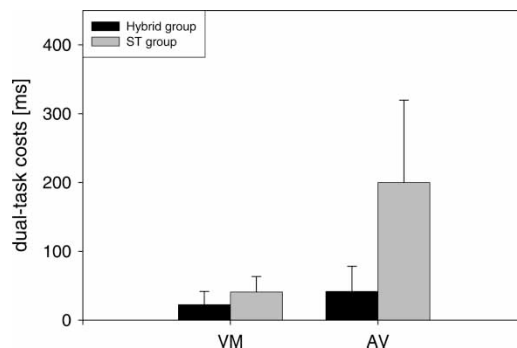


Figure 3. Dual-task cost (dual-task minus single-task reaction times) in Session 8 of the hybrid practice group (hybrid group) and the single-task practice group (ST group) for Experiment 1. VM = visual–manual task. AV = auditory–verbal task. Error bars represent standard errors.

observed,  $F(1, 14) = 15.51$ ,  $p < .001$ ,  $\eta^2 = .53$ , indicating higher error rates in single-task trials ( $M = 4.6\%$ ) than in dual-task trials ( $M = 1.9\%$ ). That is, we observed a speed–accuracy trade-off in both groups with lower RTs but higher error rates in single tasks than in dual tasks. What is important for the question concerning the acquisition of ITC is that for the visual task we found no significant dual-task specific advantage of hybrid practice over single-task practice.

*AV task.* Most importantly, a significant interaction of Trial Type  $\times$  Group on the RTs was observed in Session 8,  $F(1, 14) = 12.83$ ,  $p < .01$ ,  $\eta^2 = .47$ , indicating larger dual-task costs in the single-task group ( $M = 200$  ms),  $t(7) = 4.73$ ,  $p < .01$ , than in the hybrid practice group ( $M = 41$  ms),  $t(7) = 3.20$ ,  $p < .05$ . In detail, RTs in dual-task trials were decreased in the hybrid practice group as compared to the RTs in the single-task group,  $t(14) = 2.24$ ,  $p < .05$ , whereas we found similar single-task performance in the hybrid practice group and the single-task group,  $t(14) < 1$ . We observed no main effect of group,  $F(1, 14) = 1.96$ ,  $p > .05$ ,  $\eta^2 = .11$ , but a main effect of trial type,  $F(1, 14) = 29.81$ ,  $p < .001$ ,  $\eta^2 = .67$ . That is, we found slower RTs in dual-task trials ( $M = 503$  ms) than in single-task trials ( $M = 383$  ms) in both groups.

To rule out the possibility that the finding of decreased dual-task costs in the AV task in the hybrid practice group compared to the single-task group is based on only a few participants with mean values strongly deviating from those of the rest, we additionally conducted a nonparametric test on the dual-task RT costs. This test includes the rank of each participant according to its dual-task costs and ignores the absolute amount of costs. In this list, a lower rank value indicates a lower amount of dual-task costs. A nonparametric Mann–Whitney  $U$  test showed a significant difference between the list ranks of the hybrid practice (mean rank = 4.75) and the single-task group (mean rank = 12.25),  $p < .05$ . This test shows that the present finding of reduced dual-task costs after hybrid practice as compared to single-task practice is not the result

of only a few outlier participants with extremely low dual-task costs.

The error analysis of the AV task revealed neither effects of group and trial type nor an interaction of both factors.

## Discussion

In line with previous findings (Hazeltine et al., 2002; Schumacher et al., 2001), we found that hybrid practice strongly reduced dual-task costs in a VM task and an AV task. Nevertheless, dual-task costs were not completely eliminated after practice in the present study but remained on a small but significant level. For the visual task we found increased error rates in single-task trials during practice in both groups. This finding is consistent with previous findings using a similar dual-task situation (Hazeltine et al., 2002; Schumacher et al., 2001; Tombu & Jolicoeur, 2004) and may be explained by a reduced degree of attentiveness in visual single-task trials due to reduced processing demands (Hazeltine et al., 2002). This interpretation is consistent with a further finding of our study—that is, no such increase in OR trial error rates at the end of practice. The attentiveness is higher in OR trials than in single-task trials since this trial type comprises increased processing demands—that is, participants have to be prepared for both tasks.

Importantly, the finding that the hybrid practice group showed a better performance than the single-task group in the AV task during transfer is strong evidence pointing to the acquisition of ITC. One could argue that this finding is the result of initial differences in dual-task performance between both groups. However, an additional analysis showed that this was not the case. In particular, we found no evidence for any initial group difference in dual-task performance,  $F(1, 14) < 1$  in the VM task, nor in the AV task,  $F(1, 14) < 1$  between the two groups. These findings were the outcome of the comparison of the initial dual-task performance of the hybrid practice group with the two initial dual-task test blocks of the single-task group (see Table 2). The comparison

Table 2. Pretest reaction times and percentage errors for the visual–manual and the auditory–verbal tasks in single-task trials in single-task blocks, single-task trials in mixed blocks, and dual-task trials for the hybrid practice group and the single-task group

		<i>Experiment 1</i>		<i>Experiment 2</i>		<i>Experiment 3</i>	
		<i>Hybrid</i>	<i>ST</i>	<i>Hybrid</i>	<i>ST</i>	<i>Hybrid</i>	<i>ST</i>
VM	Single task	289 (2.5)	292 (2.2)	289 (2.5)	276 (1.7)	289 (2.5)	291 (1.4)
	OR	367 (0.8)	410 (0.0)	367 (0.8)	345 (0.5)	386 (0.8)	359 (0.4)
	Dual task	439 (5.1)	459 (6.0)	439 (5.1)	412 (4.2)	416 (6.1)	436 (5.5)
AV	Single task	571 (5.4)	606 (3.1)	571 (5.4)	587 (6.2)	571 (5.4)	584 (7.2)
	OR	786 (14.2)	771 (10.0)	786 (14.2)	742 (10.8)	792 (13.0)	757 (16.8)
	Dual task	911 (13.4)	887 (9.4)	911 (13.4)	889 (12.8)	911 (10.8)	872 (8.9)

*Note:* Pretest reaction times in ms. Percentage of errors in parentheses. VM = visual–manual task. AV = auditory–verbal task. Single task = single-task trials in single-task blocks. OR = single-task trials in mixed blocks. Dual task = dual-task trials. Hybrid = hybrid practice group. ST = single-task group.

of the VM task performance between both groups showed no statistical difference.<sup>1</sup>

Thus far, dual-task performance was compared in a dual-task situation in which the stimuli, the mappings, and the responses in the VM task, as well as in the AV task, remained unchanged. That is, the identical VM task and AV task were presented during the seven practice sessions and the final test session, Session 8, in the hybrid practice group and the single-task group. Based on these findings one cannot exclude that the observed dual-task advantage of the hybrid-training group is due to highly task-specific knowledge acquired in the specific and trained dual-task situation. To test whether the acquired ITC skill is independent of the specific stimulus and mapping characteristics of the VM task given during practice, we performed a second experiment.

## EXPERIMENT 2

To conclude that dual-task learning leads to an acquisition of task-independent knowledge

(Bherer et al., 2008), evidence is needed that ITC is not tied to specific characteristics of the component tasks. The aim of Experiment 2 was therefore to investigate whether the acquired ITC skill is independent of stimulus and mapping features of the VM task and therefore transferable to a novel dual-task situation with a changed VM task.

For that purpose, we compared two groups of participants differing in their amount of dual-task practice. One group trained two component tasks under single-task and dual-task conditions (hybrid practice group) for eight sessions. This hybrid practice group was identical to the hybrid practice group of Experiment 1. A second single-task group practised the same component tasks for the identical number of sessions as did the hybrid practice group, but only under single-task conditions (except the two mixed blocks at the beginning of practice to measure initial dual-task performance). The number of stimulus contacts was held constant between both groups. After eight practice sessions, we compared the performance of both groups of learners in a new dual-task situation, which was presented in Transfer Session

<sup>1</sup> However, as the given group sizes are relatively small, the lacking difference in the VM task between the two groups could be due to a lack of power, as was suggested by one anonymous reviewer. Therefore, one could argue that an increase of the group size might have revealed latent differences between the two groups. In order to test that, we performed an additional power analysis, which demonstrated that the finding of comparable VM task performance in both groups was quite robust. Given  $\alpha$ , power, and the effect size of the present experiment, the group factor and the interaction of group and trial type would still not reach a significant value if we were to double the number of participants in both groups (G\*Power: Faul, Erdfelder, Buchner, & Lang, 2009).

9. In Session 9, the stimulus–response mapping of the VM task was changed compared to that in the practice sessions; participants now responded to stimuli of different size (small, medium, large stimulus), which were presented at the centre of the screen with the fingers of their right hand. We also changed the stimuli in the VM task; instead of circles we presented triangles in the transfer session. If ITC is independent of the VM task presented during training, we predict reduced dual-task costs for the hybrid practice group as compared to the single-task group during transfer. In contrast, if this skill is specific to a dual-task situation with the VM task given during training, then we should find similar dual-task performance in both groups during the transfer session.

## Method

### *Participants*

The 8 participants from Experiment 1 from the Humboldt-University, Berlin, formed the hybrid practice group. In addition, a new group of 8 undergraduate students matched by age and gender (7 female, age 19–27 years, mean age: 22) to the participants of the hybrid practice group was used as the single-task group. All participants were right-handed, had normal or corrected-to-normal vision, and were naive with regard to the hypotheses of the experiment. All participants gave their written informed consent to participate in the study, which was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

### *Apparatus and stimuli*

Apparatus and stimuli were identical to those in Experiment 1, with the exception of the manipulation of the VM task in Session 9 (transfer). The stimuli and the corresponding mapping rule were changed from circles to triangles of different sizes (large, medium, or small). Triangles were presented at the central position of the screen. Participants had to respond according to the size of the triangles, using the index finger for the large, the middle finger for the medium, and the

ring finger for the small triangle. The viewing distance of 60 cm and the manual response with the right hand remained constant. The side length of the large triangle was 2.6 cm, which corresponds to 2.48° of the visual angle. The sides of the medium triangle were 1.6 cm, which corresponds to 1.52° of the visual angle, and the sides of the small triangle were 1 cm, which corresponds to 0.95° of the visual angle. One centrally presented line served as a placeholder and a warning signal. The triangle remained visible until the participant responded or until a maximum of 2,000 ms had elapsed.

### *Procedure and design*

Procedure and design were identical to those in Experiment 1 for the hybrid practice group and the single-task group, with the exception that both groups of participants conducted eight practice sessions, and the transfer was conducted in the ninth session.

## Results

In general, the results of Experiment 2 are structured in a similar way as in Experiment 1. The only exception is that the practice performance was assessed in Session 2 to Session 8, and the transfer performance was assessed in Session 9. The same outlier procedure as that in Experiment 1 was applied to the data set of Experiment 2, which resulted in the exclusion of 7.2% reverse response order trials and of 6.9% incorrect trials.

### *Hybrid practice group: Practice performance*

For the analyses of practice performance in the VM task and AV task of the hybrid practice group, see analyses of the hybrid practice group of Experiment 1.

### *Single-task group: Practice performance*

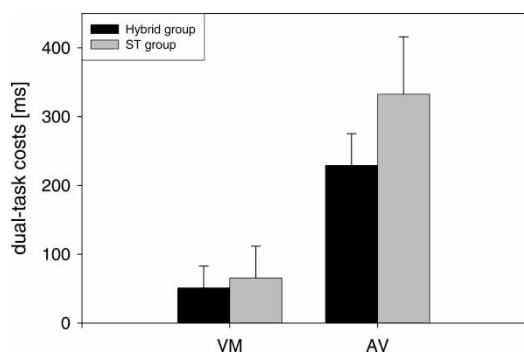
As illustrated in Figure 2, the analysis of the single-task practice data of the single-task group showed a reduction of the RTs in the VM task,  $F(1, 7) = 49.34$ ,  $p < .001$ ,  $\eta^2 = .88$ , and in the AV task,  $F(1, 7) = 171.46$ ,  $p < .001$ ,  $\eta^2 = .96$ ,

from Session 2 to Session 8. Similar to the error analysis in Experiment 1, we found a practice-related increase of the error rates in the VM task,  $F(1, 7) = 21.11$ ,  $p < .01$ ,  $\eta^2 = .75$ . However, we also found this increase in the AV task,  $F(1, 7) = 7.25$ ,  $p < .05$ ,  $\eta^2 = .51$ .

### Single-task group versus hybrid practice group: Testing for ITC

**VM task.** To test for ITC, we performed a comparison of RTs and error rates between the hybrid practice group and the single-task group in Session 9 similar to the analysis of the performance in Session 8 of Experiment 1 (Figures 2 and 4). We observed no effect of group,  $F(1, 14) = 1.12$ ,  $p > .05$ ,  $\eta^2 = .08$ , and no interaction of Group  $\times$  Trial Type,  $F(1, 14) < 1$ , for RTs. That is, the RT data of the VM task showed a similar performance level in both groups of learners. A main effect of trial type indicated different performance levels in single-task and dual-task trials across both groups of participants,  $F(1, 14) = 44.06$ ,  $p < .001$ ,  $\eta^2 = .58$ . Participants responded slower in dual-task trials ( $M = 432$  ms) than in single-task trials ( $M = 366$  ms). The identical error analysis in the VM task revealed no effect or interaction (see Table 1).

**AV task.** The dual-task performance during Transfer Session 9 was improved in the hybrid



**Figure 4.** Dual-task cost (dual-task minus single-task reaction times) in Session 9 of the hybrid practice group (hybrid group) and the single-task practice group (ST group) for Experiment 2. VM = visual-manual task. AV = auditory-verbal task. Error bars represent standard errors.

practice group, as compared to the single-task group in the AV task (Figures 2 and 4). This finding was indicated by an interaction of Trial Type  $\times$  Group,  $F(1, 14) = 7.43$ ,  $p < .05$ ,  $\eta^2 = .36$ . Here, we found decreased dual-task costs in the hybrid practice group ( $M = 228$  ms),  $t(7) = 9.33$ ,  $p < .01$ , compared to those of the single-task group ( $M = 332$  ms),  $t(7) = 11.30$ ,  $p < .01$ , during transfer. A nonparametric Mann-Whitney  $U$  test demonstrated a significant difference between the list ranks of the hybrid practice (mean rank = 5.75) and the single-task group (mean rank = 11.25),  $p < .05$ . This shows that, similar to the findings of Experiment 1, the present finding of reduced dual-task costs after hybrid practice did not result from only a few outlier participants with extremely low dual-task costs. RTs in dual-task trials and single-task trials were similar in the hybrid practice group and the single-task group,  $ts(14) < 1$ . The finding of improved dual-task performance after hybrid practice is solely reflected in dual-task costs. Generally, we found a main effect of trial type,  $F(1, 14) = 214.72$ ,  $p < .001$ ,  $\eta^2 = .94$ , reflecting faster RTs in single tasks ( $M = 365$  ms) than in dual tasks ( $M = 645$  ms). The factor *group* was not significant.

The analysis of the error rates demonstrated a main effect of trial type,  $F(1, 14) = 5.68$ ,  $p < .05$ ,  $\eta^2 = .29$ , reflecting higher error rates in dual-task ( $M = 13.0\%$ ) than in single-task ( $M = 7.1\%$ ) trials. The factor *group* and the interaction of Trial Type  $\times$  Group were not significant.

## Discussion

In Experiment 2, we tested whether ITC is independent of the specific mapping in the VM task practised during training. We compared dual-task performance between a hybrid and a single-task practice group in a dual-task transfer situation with a changed VM task. In this new dual-task transfer situation, we found evidence for improved dual-task performance in the hybrid practice group as compared to the single-task group in the AV task only, which is consistent with the findings of Experiment 1. A dual-task performance

advantage in the AV task in a changed VM task transfer situation indicates that the acquired ITC skill is not associated with the specific VM task trained during practice and that this skill is transferable to a new dual-task situation. As in Experiment 1, we found no evidence for initial group differences at the beginning of practice in the VM task,  $F(1, 14) < 1$ , nor in the AV task,  $F(1, 14) < 1$ ; this rules out that the observed advantage of the hybrid practice group in the transfer session was due to a general dual-task performance advantage of the hybrid over the single-task practice group (see Table 2).

In Experiment 2 (and also Experiment 1), the AV task remained unchanged. Thus, on the basis of the current findings one cannot exclude that the dual-task performance advantage of the hybrid practice group reflects the acquisition of an ITC skill that is tied to the specific mapping characteristics of the auditory task trained during practice. To test this assumption, we performed a final experiment in which we compared the performance of a new hybrid and a new single-task learning group in a transfer situation in which only the AV task was changed.

### EXPERIMENT 3

The aim of Experiment 3 was to investigate whether the acquired ITC skill is transferable to a dual-task situation with a new AV task mapping and therefore would reflect task-general knowledge (Schmidt & Bjork, 1992). Findings of superior hybrid practice over single-task practice in both previous experiments might alternatively be explained by the acquisition of the specific mapping characteristics of the auditory task, which remained unchanged during the entire practice situation, as well as during transfer in Experiment 2. In Experiment 3, we changed the task features of the AV task between practice and transfer and held the VM task constant. As a special requirement for the transfer manipulation in the AV task, we aimed to apply a manipulation, which should lead to RT increases in the changed AV task, which are numerically in a similar range

as the changes in the VM task of Experiment 2. Such a titration of the difficulty of the transfer manipulations across component tasks is necessary because the initial difficulty level of the two component tasks in the paradigm of Schumacher et al. (2001) is not equal; note that in this paradigm a VM task with a highly spatially compatible and highly natural stimulus–response mapping is combined with an AV task that is characterized by a rather arbitrary but compatible stimulus–response mapping (Kornblum, Hasbroucq, & Osman, 1990). Such basic differences may contribute to the different degrees of automatization, which can be observed for the VM and the AV task even at the end of practice, as indicated by the numerical differences in dual-task costs. Therefore, in Experiment 3 we decided to change the stimulus–response mapping of the AV task only. Prior experiments indicated that a change of the mapping rule in the AV (without additional change of the stimuli) would lead to an increase of the RTs in the changed AV task (RT increase 173 ms), which is comparable to the amount of the RT increase after the VM task change in Experiment 2 (169 ms). If the acquired ITC skill is independent of the specific AV task mapping given during training, then we should find an advantage for the hybrid practice group over the single-task group (i.e., reduced dual-task costs) in the manipulated AV dual-task situation. In contrast, if the acquired skill is tight to the specific AV task mapping experienced during practice, we expect similar single-task and dual-task performance in both groups of learners during transfer.

### Method

#### *Participants*

The 16 participants were undergraduate students from the Humboldt-University, Berlin. The hybrid practice group comprised 8 students (4 female, age 21–30 years, mean age: 25.5), while 8 age-balanced students (7 female, age 18–27 years, mean age: 22.4) participated in the single-task group. All participants were right-handed, had normal or corrected-to-normal vision, and

were naive with regard to the hypotheses of the experiment. All participants gave their written informed consent to participate in the study, which was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

#### *Apparatus, stimuli, procedure, and design*

Apparatus, stimuli, procedure, and design were identical to those in Experiment 2, with the exception of the AV task manipulation in Session 9 (transfer phase). During this phase, the mapping of the AV task was changed. Participants now had to respond by saying “TWO” for the low-frequency tone, “ONE” for the middle-frequency tone, and “THREE” for the high-frequency tone (German: “ZWEI”, “EINS”, and “DREI”), which resembles a manipulation of the stimulus–response mapping of the AV task.

## Results

Statistical analyses and the results structure are similar to those in Experiment 2. The same outlier procedure as that in previous experiments was applied to the data set of Experiment 3, which resulted in the exclusion of 3.0% reverse response order trials and 5.3% incorrect trials.

#### *Hybrid practice group: Practice performance*

The analyses of practice performance for RT data showed a Session  $\times$  Trial Type interaction in the VM task,  $F(2, 14) = 13.32$ ,  $p < .001$ ,  $\eta^2 = .69$ . The dual-task costs in Session 2 ( $M = 79$  ms),  $t(7) = 4.19$ ,  $p < .01$ , were eliminated in Session 8,  $t(7) = 1.88$ ,  $p > .05$ . Similarly, we found a difference between dual-task trials and OR trials at the beginning of practice (Session 2:  $M = 45$  ms),  $t(7) = 2.83$ ,  $p < .05$ , which was eliminated at the end of practice (Session 8),  $t(7) = 2.00$ ,  $p > .05$ .

As illustrated in Table 1, an identical analysis of the error rates demonstrated an interaction of Session  $\times$  Trial Type in the VM task,  $F(2, 14) = 2.64$ ,  $p < .01$ ,  $\eta^2 = .39$ , indicating that the dual-task costs in Session 2 ( $M = 3.9\%$ ),  $t(7) = 2.69$ ,  $p < .05$ , disappeared in Session 8,  $t(7) =$

1.71,  $p > .05$ . We found no difference between the error rates of dual-task trials and those of OR trials at the beginning,  $t(7) = 1.76$ ,  $p > .05$ , and at the end of practice,  $t(7) = 1.83$ ,  $p > .05$ .

The analysis of the AV RT data also showed an interaction of Session  $\times$  Trial Type,  $F(2, 14) = 16.18$ ,  $p < .001$ ,  $\eta^2 = .74$ , indicating that the dual-task costs decreased from Session 2 ( $M = 186$  ms),  $t(7) = 10.68$ ,  $p < .001$ , to Session 8 ( $M = 48$  ms),  $t(7) = 4.28$ ,  $p < .01$ . In addition, there was also a decrease of the RT difference between dual-task trials and OR trials from Session 2 ( $M = 81$  ms),  $t(7) = 4.79$ ,  $p < .01$ , to Session 8 ( $M = 21$  ms),  $t(7) = 3.48$ ,  $p < .05$ .

There was no interaction of Session  $\times$  Trial Type in the error rates of the AV task.

#### *Single-task group: Practice performance*

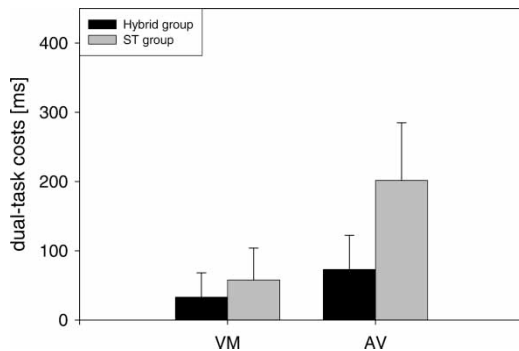
Similar to the previous experiments, we found a practice-related reduction of single-task RTs in the VM task,  $F(1, 7) = 48.84$ ,  $p < .001$ ,  $\eta^2 = .87$ , and in the AV task,  $F(1, 7) = 62.01$ ,  $p < .001$ ,  $\eta^2 = .90$ , in Experiment 3. However, we found a practice-related increase of the error rates in the VM task,  $F(1, 7) = 21.11$ ,  $p < .01$ ,  $\eta^2 = .75$ . The error analysis in the AV task showed no practice effect,  $F(1, 7) < 1$ .

#### *Single-task group versus hybrid practice group:*

##### *Testing for ITC*

*VM task.* The interaction of Group  $\times$  Trial Type in the RT data,  $F(1, 14) = 1.47$ ,  $p > .05$ ,  $\eta^2 = .10$ , was not significant (Figure 5). That is, the hybrid practice group did not reveal improved performance in either single-task or dual-task situations of the VM task compared with the single-task group. A main effect of trial type indicated a performance difference in single-task and dual-task trials across both groups of participants,  $F(1, 14) = 19.68$ ,  $p < .001$ ,  $\eta^2 = .58$ . Participants responded slower in dual tasks ( $M = 285$  ms) than in single tasks ( $M = 240$  ms). We observed equal performance levels in both groups of learners,  $F(1, 14) < 1$ .

The identical analysis of the error rates showed increased error rates in single tasks ( $M = 5.4\%$ ) than in dual tasks ( $M = 2.0\%$ ), as indicated by a



**Figure 5.** Dual-task cost (dual-task minus single-task reaction times) in Session 9 of the hybrid practice group (hybrid group) and the single-task practice group (ST group) for Experiment 3. VM = visual-manual task. AV = auditory-verbal task. Error bars represent standard errors.

significant effect of trial type,  $F(1, 14) = 8.63$ ,  $p < .05$ ,  $\eta^2 = .38$ . Neither the factor Group nor the interaction of Group  $\times$  Trial Type reached the level of significance. Thus, we found no dual-task-specific difference in the VM task after hybrid practice and after single-task practice.

*AV task.* As illustrated in Figures 2 and 5, we observed a main effect of Group on the RTs,  $F(1, 14) = 8.09$ ,  $p < .05$ ,  $\eta^2 = .37$ , in which the hybrid practice group ( $M = 488$  ms) showed faster responses than single-task learners ( $M = 646$  ms). We also found a difference between single-task trials ( $M = 498$  ms) and dual-task trials ( $M = 636$  ms) across both groups,  $F(1, 14) = 64.29$ ,  $p < .001$ ,  $\eta^2 = .82$ . Importantly, both effects were qualified by a significant interaction of Trial Type  $\times$  Group in Session 9,  $F(1, 14) = 14.14$ ,  $p < .01$ ,  $\eta^2 = .50$ , indicating smaller dual-task costs of the hybrid practice group ( $M = 70$  ms),  $t(7) = 4.17$ ,  $p < .01$ , than of the single-task group ( $M = 202$  ms),  $t(7) = 6.85$ ,  $p < .001$ . A nonparametric Mann-Whitney  $U$  test demonstrated a significant difference between the list ranks of the hybrid practice (mean rank = 5.13) and the single-task group (mean rank = 11.88),  $p < .05$ . This test shows that the present finding of reduced dual-task costs after hybrid compared to single-task practice is not the result

of only a few outlier participants with extremely low dual-task costs. RTs in dual-task trials were decreased in the hybrid practice group as compared to the RTs in the single-task group,  $t(14) = 3.59$ ,  $p < .01$ . However, we found a similar performance of the hybrid practice group and the single-task group in single-task trials,  $t(14) = 1.73$ ,  $p > .05$ .

The error analysis of the AV task revealed a main effect of trial type,  $F(1, 14) = 16.94$ ,  $p < .001$ ,  $\eta^2 = .55$ , with more errors in dual-task trials ( $M = 13.9\%$ ) than in single-task trials ( $M = 9.2\%$ ). The factor group and the interaction of Group  $\times$  Trial Type were not significant.

## Discussion

In Experiment 3, we investigated whether ITC is independent of the specific AV task experienced during practice. This is because improved performance after hybrid practice could have been explained by the acquisition of an ITC skill that is tied to the specific mapping characteristics of the AV task present during training. Contrary to this and in line with our previous experiments, we found a dual-task performance advantage in the hybrid practice group as compared to the single-task group in the AV task during a transfer session in which the mapping of the AV task was changed. Further, we did not find evidence for any initial group differences in the VM task,  $F(1, 14) < 1$ , nor in the AV task,  $F(1, 14) = 1.55$ ,  $p > .05$  (see Table 2), which rules out that possible initial group differences in dual-task performance may have caused the observed differences in dual-task performance during transfer.

An issue that needs to be discussed is that unlike in Experiment 2 we did not manipulate the stimulus information but only the stimulus-response mapping in Experiment 3, which was necessary to ensure comparable difficulty levels for the transfer manipulations. According to a number of studies on learning-related changes in choice reaction tasks (e.g. Pashler & Baylis, 1991; Ruthruff et al., 2006), practice effects in choice tasks are located at the central stages rather than at the perceptual stages of a task;



given that the current transfer manipulation affected primarily the central stages of the AV task and given the large effect size of the hybrid training advantage, it seems unlikely that the hybrid training advantage over the single-task training would have disappeared if we had manipulated the tones in addition to the mapping of the AV task.

In sum, the findings of Experiment 3 are consistent with the assumption that the participants do acquire an ITC skill during hybrid practice that does not depend on the specific characteristics of the AV task experienced during training.

## GENERAL DISCUSSION

The goal of this study was to test whether intertask coordination (ITC) is acquired during extensive hybrid training using a dual-task situation of Schumacher et al. (2001) in which a VM task and an AV task have to be performed simultaneously. Additionally, we tested whether this skill is independent of the specific component VM and AV tasks presented during practice and is thus transferable across different dual-task situations.

Several important findings were obtained in the present study. First and most important for the research question about ITC is the finding that dual-task performance in the hybrid practice groups was better than that in single-task groups. This dual-task advantage in the hybrid practice groups was consistently found in all three experiments. These findings suggest that ITC is acquired under hybrid practice, a combination of single-task and dual-task practice. Second, we found a dual-task performance advantage in a transfer situation in which the same tasks were used that were presented during practice (Experiment 1), in situations in which specific task characteristics of the VM task (Experiment 2) or of the AV task (Experiment 3) were changed compared to training. The findings from dual-task situations with changed component tasks suggest that the ITC skill acquired during extended dual-task training is not tied to

the specific task characteristics of the VM task or the AV task.

A third important finding was that the dual-task practice advantage in all experiments was present in the RT data of the AV task, only. As the latter finding is essential for the definition of the specific skill acquired during hybrid practice, we come back to an extensive discussion of this finding relating ITC to recent dual-task models. It is important to note that possible initial dual-task performance differences between groups cannot account for the finding of ITC acquisition under hybrid practice. Initial task performance of the hybrid practice and single-task groups did not differ in all three experiments.

### ITC: A product of hybrid training and equal priority instructions?

The present findings are in line with the assumption that hybrid practice, combining the advantage of single-task and dual-task training, is effective for promoting the acquisition of an ITC skill (Kramer et al., 1995). Single-task training can lead to automaticity of the given individual component tasks, and dual-task training can lead to the acquisition of coordination strategies required in a dual-task situation. Since Ruthruff et al. (2006) did not find a dual-task practice advantage when using a fixed training strategy with a PRP paradigm, our findings show the relevance of the specific priority instructions used during dual-task practice. Using equal priority instructions during training in combination with hybrid practice seems to provide sufficient flexibility in task processing that is needed to acquire ITC. In particular, while single-task blocks require the exclusive processing of either the VM or the AV task, the type of task processed is uncertain in mixed blocks; this block type requires to flexibly switch between the VM and AV task processing as well as to the processing of dual tasks. In contrast, a constant fixed priority on Task 1 during dual-task practice (Ruthruff et al., 2006) may not provide enough variability during practice to acquire ITC skills. Dual-task practice with fixed priority entails no uncertainty of the upcoming

task presentation and the order of their processing. One may argue that such a certainty of the presented tasks and task order does not lead to the acquisition of ITC skills while hybrid practice with uncertainty of the presented tasks does so.

### Theoretical implications for dual-task models

In the following, we discuss how the present data showing evidence for an acquisition of ITC under hybrid practice might be integrated into various models of dual-task performance. According to the RSB model (Pashler, 1994; Pashler & Johnston, 1998) the processing bottleneck at the RS stage is a structural limitation of the cognitive system. Derived from the RSB model of dual-task processing, Ruthruff and colleagues (Lien, Ruthruff, & Johnston, 2006; Ruthruff et al., 2003; Schubert, 2008) presented the latent bottleneck model as a possible explanation for the finding of an extreme dual-task cost reduction after practice. This model assumes that bottleneck processing stages in the component tasks are still present but latent because they are extremely and asymmetrically shortened as a result of practice. At the end of practice, processing of RS stages in the two tasks is temporally scheduled in a way that avoids any temporal overlap between capacity-limited stages. This leads to a reduction in dual-task costs mainly in Task 2 in dual-task situations. Recent studies have provided first evidence that bottleneck stages may still be present but latent in practised dual tasks (Anderson, Taatgen, & Byrne, 2005; Liepelt, Fischer, Frensch, & Schubert, 2011; Ruthruff et al., 2003, 2006). The assumption of a latent bottleneck is in line with our finding of an extreme and sometimes complete dual-task cost reduction. Within the latent bottleneck model, improved ITC as found in the present study might represent an accelerated switching operation (Band & van Nes, 2006; Lien et al., 2003), which might play an important role for the development of a latent bottleneck after dual-task practice (e.g., Maquestiaux et al., 2004). In detail, after selection of an appropriate

response at the Task 1 RS stage, a switching operation may be required. During switching the task rules can be activated that map stimuli onto responses in Task 2. During this operation, rules for Task 2 must be loaded into working memory or reestablished after the RS stage in Task 1 is finished. One plausible way how dual-task practice might help to establish a latent bottleneck is by accelerating the switching operation between RS stages in both tasks (Band & van Nes, 2006; Lien et al., 2003), which would reduce any postponement of the RS stage in Task 2. In the single-task training group, such a switching operation may be delayed, because switching was never practised, thus leading to increased dual-task costs in Task 2. Similar to previous studies (e.g., Hazeltine et al., 2002; Schumacher et al., 2001; Tombu & Jolicoeur, 2004), we found the AV task to have slower reaction times than the VM task. Accordingly, participants might perform the RS stage of VM task first and perform the RS stage of AV task second in dual-task situations (Hazeltine et al., 2002; Ruthruff et al., 2003). An accelerated speed-up switch would allow a faster initiation of RS in the AV task (i.e., Task 2) after the end of the RS stage in the VM task (i.e., Task 1). In line with this assumption, in all three experiments, we consistently found larger dual-task costs in the AV task in the single-task group than in the hybrid practice group.

In Experiments 2 and 3 of the present study, we found a dual-task performance advantage for dual-task situations including a manipulated VM task (Experiment 2) or AV task (Experiment 3). Taking the idea of an accelerated speed-up switching operation in the context of the latent bottleneck model, the findings of these experiments argue against the assumption that an improved switching skill (Band & van Nes, 2006) is tied to the specific VM task or to the specific AV task present during practice. The ITC skill seems to be independent of specific characteristics of the component tasks presented during hybrid practice. This interpretation is in line with the assumption of a task-general switching skill proposed by a recent study showing transfer effects from practised situations of task switching to a novel

task-switching situation after practice (Korbach & Kray, 2009). More general, the present data are in line with the assumption that such a switching skill may be defined as an executive process of attention control that is improved through variable practice (Gopher, 1993).

As the RSB model represents a special case of the capacity-sharing model in which the processing capacity is allocated fully to Task 1, the capacity-sharing model is also able to account for the current findings of dual-task cost reduction during practice. According to the capacity-sharing model, the advantage of hybrid practice in the AV task can be viewed as an improved reallocation of capacity to Task 2 after processing of Task 1 central stage is finished. Single-task training would not lead to improved capacity reallocation since central stages in both tasks have only been trained in isolation.

According to the EPIC model (Meyer & Kieras, 1997a, 1997b), extended dual-task practice may lead to a more daring task-scheduling strategy. This strategy would increase the amount of parallel processing of Task 1 and Task 2 stages. Given the finding of improved dual-task processing in the AV task after hybrid practice, our findings may suggest that hybrid practice leads to a change in subjects' processing strategy from a cautious to a more daring login of AV task processing. When changing subtasks, people in the hybrid group may profit from their adopted strategies transferring them to the new dual-task situation. In contrast to that, people in the single-task training group would adopt a more cautious task processing when confronted with a changed dual-task situation. This cautious strategy reduces the amount of parallel processing of Task 1 and Task 2 stages and leads to higher dual-task costs. This assumption might explain the improved dual-task performance after hybrid practice when compared to single-task practice in the three present experiments in the context of EPIC.

A single-task automatization model (e.g., Ruthruff et al., 2006) can explain the observed shortenings of reaction times in both tasks, also reducing interference between two tasks in dual-

task situations. However, the assumption of single-task automatization, thought to eliminate processes that compete for limited capacity (e.g., Johnston & Delgado, 1993), cannot explain the difference in dual-task costs that we found between the hybrid practice and the single-task practice groups during transfer. We kept the number of stimulus contacts equal in both groups allowing an equal level of single-task automatization (Kramer et al., 1995) in both groups. Furthermore, the single-task performance in the RT and error data in both groups was similar at the end of training, reflecting a similar single-task performance level. Even though single-task practice improves task processing in both component tasks, an automatization model has to be rejected for explaining the finding of an ITC skill under hybrid practice.

We adapted the dual-task design from Schumacher et al. (2001), including a VM task and an AV task to test for the acquisition of ITC after practice. We used this paradigm because it provides optimal conditions (i.e., SOA = 0 ms, equal priority, and bonus payments) to achieve dual-task cost reduction with a manageable amount of practice (five to eight hours with each participant). However, the applied paradigm seems also to be restricted. The VM task is the faster task and the AV task the slower task, meaning that we are unable to separate conclusions about the acquisition of ITC skills improving either Task 1 processing or Task 2 processing from conclusions about the acquisition of ITC based on task modality (i.e., skills improving tasks with visual input/manual output or tasks with auditory input/verbal output). Therefore, the present findings might not be easily generalizable to task situations with alternative task sequences, which seems, however, a promising question for future research. Testing transfer of skilled performance in task situations that structurally differ from the practised task situation, as, for example, using different stimulus and response modalities between practice and transfer, may allow a further distinction between near and far ITC transfer effects (Barnett & Ceci, 2002; Klauer, 2001).

A further important finding of the present study is that extended dual-task practice in the hybrid practice groups reduced dual-task costs in the VM task and the AV task to a great extent. After eight sessions of practice, RT differences between dual-task and single-task trials were greatly reduced, but residual dual-task costs remained. This suggests that findings of a complete dual-task cost reduction are not easily obtained as a result of dual-task practice (Schumacher et al., 2001), which is in line with a range of previous findings (Hazeltine et al., 2002; Tombu & Jolicoeur, 2004). 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 pay-off 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 pay-off 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 by Schumacher and colleagues in contrast to the small residual dual-task costs we found at the end of practice.

## CONCLUSIONS

The present study was designed to test whether task coordination can be acquired during dual-task training and whether such a skill is independent of the specific component tasks. We found evidence for the acquisition of intertask coordination under hybrid practice conditions combining dual-task and single-task practice. Furthermore,

novel dual-task situations showed that an acquired coordination skill is not fully task-specific.

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