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Effects of extensive dual-task practice on processing stages in simultaneous choice tasks

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Abstract Schumacher et al. Psychological Science 12:101–108, (2001) demonstrated the elimination of most dual-task costs ("perfect time-sharing") after extensive dual-task practice of a visual and an auditory task in combination. For the present research, we used a transfer methodology to examine this practice effect in more detail, asking what task-processing stages were sped up by this dual-task practice. Such research will be essential to specify mechanisms associated with the practice-related elimination of dual-task costs. In three experiments, we introduced postpractice transfer probes focusing on the perception, central response-selection, and final motor-response stages. The results indicated that the major change achieved by dual-task practice was a speed-up in the central response-selection stages of both tasks. Additionally, perceptual-stage shortening of the auditory task was found to contribute to the improvements in time-sharing. For a better understanding of such time-sharing, we discuss the contributions of the present findings in relation to models of practiced dual-task performance.

Keywords Dual-task performance · Practice effects · Processing stage shortening

When people execute two tasks simultaneously, performance in one or in both of the tasks is often impaired, as indicated by an increase in processing time and/or in error rate (e.g., Kahneman, 1973; Pashler, 1994; Schubert, Fischer, & Stelzel, 2008; Telford, 1931; Welford, 1952). Performance impairments in dual-task relative to single-task contexts are referred to as *dual-task costs* and have been attributed to processing limitations at the response-selection stage (Pashler, 1994; Schubert, 1999). A typical explanation for dual-task costs is that the response-selection process in one task is postponed until response selection in the other task has been completed. This postponement has been attributed to structural (Pashler, 1994) and/or strategic (Meyer & Kieras, 1997) processing limitations within, as well as to cross-talk (e.g., Hommel, 1998; Huestegge & Koch, 2009) or capacity sharing between, the tasks (Tombu & Jolicœur, 2004).

A number of studies have shown that dual-task processing is optimized as a result of extended dual-task practice (e.g., Ahissar, Laiwand, & Hochstein, 2001; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Liepelt, Strobach, Frensch, & Schubert, 2011; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Spelke, Hirst, & Neisser, 1976; Van Selst, Ruthruff, & Johnston, 1999). In some cases, practice leads to a strong reduction, and even to a complete elimination, of apparent dual-task costs. For example, Schumacher et al. (2001) asked participants to perform a dual-task paradigm consisting of a visual–manual (referred to as the *visual task*) and an auditory–verbal (referred to as the *auditory task*) choice reaction task. In

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the visual task, participants responded manually with keypresses to the spatial position of visually presented circles. In the auditory task, they responded by saying “one,” “two,” or “three” to the pitch of three different tones. Dual-task costs, as measured by differences between reaction times (RT) in the dual-task and single-task trials, were relatively high at the beginning of learning. However, after extended practice these costs were eliminated, suggesting a tremendous optimization of dual-task processing and providing evidence for *perfect time-sharing*.

Findings like those of Schumacher et al. (2001)—with large dual-task costs at the beginning of practice followed by major reductions in costs after extended practice—naturally raise the question of what kind of learning processes are responsible for the improvements. Recent studies have provided evidence for optimization of intertask coordination processes as a result of extended dual-task practice (Liepelt et al., 2011; Strobach, Frensch, Soutschek, & Schubert, 2012) leading to optimized task scheduling of the dual task. However, to reach near-perfect, or even perfect, time-sharing, changes within the component tasks would also have to occur. In the last decades, a number of studies have suggested that this sort of component task optimization may result from dual-task as well as single-task practice (Ahissar et al., 2001; Maquestiaux, Laguë-Beauvais, Bherer, & Ruthruff, 2008; Ruthruff et al., 2001, 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006; Sangals, Wilwer, & Sommer, 2007; Van Selst et al., 1999). However, it is relatively unclear which specific stages within the component tasks are optimized and shortened as a result of dual-task practice: the initial perception, central response-selection, or final motor stages, or a combination of these stages (Pashler & Baylis, 1991).

The aim of the present study was to explore the specific loci of stage shortening within two tasks that are optimally designed for a practice-related minimization of dual-task costs by creating conditions that minimize possible peripheral and strategic interference between the tasks. The latter consideration is important, because only under such optimal conditions may the reduction of dual-task costs occur in its purest form, while dual-task contexts not avoiding such sources of interference may not allow for revealing the whole potential of practice-related stage shortening in dual-task contexts (Meyer & Kieras, 1999). In the latter case stage shortening may not be complete, either because of remaining interference between the tasks or because processing times in the two tasks have not reached the possible minimum level. The characteristics of the task context of Schumacher et al. (2001) seem qualified for investigating the reduction of dual-task costs under optimal conditions. It obeys the conditions and requirements that were formulated by Meyer and Kieras (1999, p. 54) as being most optimal for decreasing the amount of dual-task costs:

> (Condition 1) participants are encouraged to give the tasks equal priority; (Condition 2) participants are expected to perform each task quickly; (Condition 3) there are no constraints on temporal relations or serial order amongst responses; (Condition 4) different tasks use different perceptual and motor processors; and (Condition 5) participants receive enough practice to compile complete production rule sets for performing each task.

The design of Schumacher et al. included manual and verbal response modalities that seem to provide optimal conditions for dual-task performance (e.g., Ruthruff et al., 2001), particularly in combination with compatibly paired input modalities (i.e., visual and auditory; Hazeltine, Ruthruff, & Remington, 2006). While studies adopting these characteristics for optimal dual-task performance have shown complete or almost complete reductions of dual-task costs (e.g., Hazeltine, Teague, & Ivry, 2002; Strobach, Frensch, Müller, & Schubert, 2012a, b; Tombu & Jolicœur, 2004), prior studies not obeying them did not (e.g., no equal task priorities—Kamienkowski, Pashler, Sigman, & Dehaene, 2011—or similar motor processors—Sangals et al., 2007).

Possible loci for the reduction of processing time in the component tasks: Evidence from dual-task studies

Some previous studies have already addressed the question of the locus of practice effects in dual-task processing (Kamienkoswki et al., 2011; Ruthruff et al., 2001, 2006; Sangals et al., 2007; Van Selst et al., 1999). For example, Ruthruff et al. (2006) addressed this question by comparing the performance of three groups of participants under different learning conditions: While Group 1 practiced an auditory–verbal (Task 1) and a visual–manual (Task 2) task for eight sessions, Group 2 practiced only Task 1 and Group 3 practiced only Task 2, for the same amount of time. In the ninth session, all three groups performed the same dual-task context as Group 1 had performed during practice. One of the main findings of Ruthruff et al. (2006) was similar reductions of the dual-task costs of Task 2 in the dual-task-learning Group 1 and in Group 2, who practiced only Task 1 (Group 3 still showed increased dual-task costs). In addition, the authors found that the practice-related shortening of the processing time in Task 1 was closely related to the practice-related reduction of these costs. Presuming a processing limitation at the central response-selection stage, the authors interpreted these findings with the assumption that the practice-related optimization of dual-task processing is related to the reduction of the processing time of the premotor stages in the component tasks.

However, the findings provided no conclusive evidence about the location of practice-related stage shortening within the task-processing streams. In fact, the findings of Ruthruff et al. (2006) do not clarify which of the premotor stages could have been shortened; the speed-up could have occurred at the perception stage, the response-selection stage, or at a combination of both stages. The same is true for studies in which the lateralized readiness potential has been used in the context of dual-task learning to show practice-related reductions at premotor stages of the component tasks (e.g., Sangals et al., 2007). Furthermore, all practice groups in the study by Ruthruff et al. (2006) still demonstrated substantial dual-task costs at the end of practice. Thus, the dual-task practice that they applied may not have enabled the reduction of dual-task costs under optimal conditions and may not be qualified to reveal the whole potential of practice-related stage shortening in dual-task contexts.

Possible loci for the reduction of processing time in the component tasks: Evidence from single-task studies

For the case of training single tasks, Pashler and Baylis (1991) proposed a transfer logic that may be applied to dual-task contexts, as well, and that may allow one to specify the possible loci of practice-related stage shortening beyond the findings of earlier dual-task practice studies. Pashler and Baylis presented new stimuli, new rules for mapping the stimuli to the motor responses, and/or new motor responses in several transfer conditions after extended single-task practice of a visual–manual symbol-mapping task; the manipulations that they applied focused on testing possible stage shortening at the perception, response-selection, or motor stages, respectively. The authors assumed that as a result of practice, the duration of the entire processing chain would shorten in choice RT tasks, which would result from the acquisition of or improvement in certain processing routines that might be located at the perception, response-selection, and/or motor stages of the tasks. To identify the particular processing stages that would potentially undergo practice-related shortening, the authors proposed manipulations after practice targeting the processing routines at these separate processing stages in a subsequent transfer phase. An important characteristic of these manipulations was that they were selected such that the specific targeted processing routine might or might not be applied anymore in the transfer context. The transfer manipulation would lead to an increase in processing time if participants could not use a processing routine anymore that was speeded up during earlier practice. In this case, the particular stage associated with this routine was assumed to contribute to the practice-related shortening of the component task. On the other hand, if learning did not shorten a specific processing routine, no manipulation-related increase in processing time would be expected; in this case, the manipulation would not affect processing routines that were shortened as a result of practice. If so, no conclusive evidence would emerge that potential changes in the time to perform the specific processing stages had significantly contributed to the reduction of the overall task-processing time.

For assessing a speed-up of the perceptual identification of visually presented digits, Pashler and Baylis (1991) presented the digits 2 and 7 (called *old information*) during the learning phase, which had to be responded to by pressing certain finger responses. In the transfer context, the authors presented new digits (e.g., 4 and 9), and participants responded with the same motor responses (finger) as for the old digits. If practice had led to a speed-up of specific processing routines that allowed for the perceptual identification of the digits, the introduction of the new digits should cause an increase in the processing time as compared to the task context with old stimuli. Pashler and Baylis reported no decisive slowing after the change and, therefore, ruled out the assumption of a perceptual speed-up after practice in choice RT tasks.

Processes at the central stage were manipulated by the introduction of new mapping rules from stimuli to the responses in an additional transfer condition. That is, the same stimulus categories appeared during transfer, but each stimulus was mapped onto a different motor response as compared to the learning context. Pashler and Baylis (1991) found a dramatic increase in RTs after transfer and concluded that processes associated with response selection showed a strong shortening of the processing time during practice.

Finally, manipulation of the motor response execution stage was achieved via a translation of the specific motor responses from a practiced to an unpracticed hand. This type of translation of the motor responses allowed for specifying whether participants had optimized the motor programs that were related to the specific muscles of the motor responses. However, the findings did not reveal any increase in processing times after transfer, suggesting that the execution of the specific motor responses had not been shortened as a result of practice. Summing up their findings, Pashler and Baylis (1991) suggested that prolonged practice of sensorimotor tasks leads to stage shortening that is primarily located at the central processing stage.

However, despite the evidence provided by Pashler and Baylis (1991), the assumption of a single locus of possible practice effects at the central stage may not be sufficient to account for all possible loci of processing advantages after practice. There may be several reasons: On one hand, other single-task practice studies than that of Pashler and Baylis have already shown additional loci of processing stages, and on the other, a generalization of findings from single-task to dual-task studies may be premature.

In detail, other single-task studies have revealed that learning-related changes might be located at the perception stage, as well (e.g., Ahissar & Hochstein, 1993; Allen, Ruthruff, Elicker, & Lien, 2009; Hawkey, Amitay, & Moore, 2004; Webb, Roach, & McGrew, 2007). This was made evident in tasks using visual (Ahissar & Hochstein, 1993) and auditory (e.g., Hawkey et al., 2004) stimuli; the finding of auditory perception-stage shortening, as compared to a lack of shortening in the visual task of Pashler and Baylis (1991), indicates that the range of generalizing the findings of stage shortening between tasks with different modalities is limited. Therefore, in a dual task, it is essential to systematically test stage shortening in both visual and auditory component tasks—as, for example, were combined in the dual-task context of Schumacher et al. (2001). Furthermore, the amount of practice in the Pashler and Baylis study was rather moderate as compared to other learning studies, including the dual-task learning studies that led to perfect time-sharing. Thus, a larger amount of practice than was available in the Pashler and Baylis study might result in additional loci of stage shortening.

Moreover, for the particular case of stage shortening in dual-task contexts, it is not clear whether we can generalize from the findings of Pashler and Baylis (1991) to dual-task contexts. As component-task learning seems to benefit from undivided attention, the strong processing demands in situations with simultaneously presented component tasks may prevent, or at least slow, practice-related improvements of the component tasks in dual-task contexts (Kramer, Larish, & Strayer, 1995). Empirical evidence for impaired component-task learning in a dual task was provided by Ahissar et al. (2001), who investigated the influence of practice on a situation combining an orientation feature detection and a letter identification task. In this context, no significant learning occurred in the orientation task at the beginning of practice. The practice-related improvement of the orientation feature detection task occurred only after participants had fully improved the letter identification task, which is suggestive of impaired component-task learning in the case of simultaneous tasks (see also Brown, 1998). Further evidence for impaired task learning under conditions of divided attention has come from studies on serial motor reaction task learning (Frensch, Wenke, & Rünger, 1999; Nissen & Bullemer, 1987; Schumacher & Schwarb, 2009). In these studies, a lesser amount of knowledge about sequence information was acquired after dual-task than after single-task practice. These findings demonstrated that our account would have limited validity if we were to conclude about stage shortening by generalizing findings from single-task learning to dual-task contexts. Consequently, it would be essential to investigate possible stage shortening specifically in dual-task contexts, and to focus especially on dual-task contexts that would reflect the conditions for optimal dual-task processing formulated by Meyer and Kieras (1999; Ruthruff et al., 2003).

Applying or adapting the dual-task context of Schumacher et al. (2001), we assessed practice-related changes at the perception and motor-processing stages of the auditory task in Experiment 1, and in Experiment 2 we investigated practice-related changes at the corresponding processing stages in the visual task. Experiment 3 tested central stage shortening in the auditory and visual tasks. We conducted these three experiments with independent groups of participants and applied the manipulation logic of Pashler and Baylis (1991) in order to investigate the loci of possible shortening of processing times by comparing the RTs in the component tasks before and after the transfer manipulations. In addition to practice effects on stage shortening in dual-task contexts, we also analyzed possible shortenings in the single task.

Experiment 1

Participants initially performed eight sessions of dual-task practice (as in Schumacher et al., 2001), followed by two transfer sessions (Sessions 9 and 10) in which we tested for possible stage shortening at the perceptual and motor stages of the auditory task (see Table 1).

To assess a possible practice-related speed-up due to improved stimulus identification, we intermixed old auditory stimuli (e.g., sine-wave tones) and new, unpracticed auditory stimuli (e.g., square-wave tones) in Sessions 9 and 10. Whereas the two types of auditory stimuli differed in timbre, both frequency and volume remained constant. We particularly selected the timbre information to investigate perceptual-stage shortening because this type of information has little relevance for the mapping of stimuli onto responses (e.g., in tone–pitch discrimination; Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006) and should not affect the processing time of other task stages, such as the response-selection stage. In fact, the old and new auditory stimuli belonged to the same task-relevant categories of low, middle, and high tones as in Pashler and Baylis (1991).

In order to assess possible reductions of the processing time in the motor-response stage, we manipulated the response

Table 1 Overview of the practice and task manipulations in Experiments 1 and 2

Session	Description
Session 1	Single-task practice
Sessions 2–8	Single-task practice and dual-task practice
Session 9	Perception-stage manipulation
Session 10	Perception-stage manipulation/Motor-stage manipulation

Manipulation effects for perceptual information and motor information in Session 9 and/or Session 10 were analyzed in order to assess stage shortening at the perception and motor stages of the tasks. Earlier versions of this article included tests on central-stage shortening (i.e., a central-stage manipulation) in Experiments 1 and 2. These tests were performed after two additional practice sessions (11 and 12) after the perception- and motor-stage manipulations (Sessions 9 and 10), in a final Transfer Session 13. Because of the more elaborate testing of central-stage shortening in Experiment 3, the data from Sessions 11 to 13 of Experiments 1 and 2 were excluded from the final data set information in the auditory task. We changed the verbal responses from the practiced number words (e.g., "one," "two," and "three") in Session 9 to new, unpracticed number words (e.g., "eleven," "twelve," and "thirteen") in Transfer Session 10. With this type of manipulation, we aimed to keep constant the relations between the number values (i.e., a small, a middle, and a large number with a difference of 1 between these numbers), which did not affect the processes of alternative stages (e.g., the response-selection stage; Hazeltine, Aparicio, Weinstein, & Ivry, 2007). In fact, we exclusively changed the specific verbal motor programs at the motor stage of the auditory task (Levelt, Roelofs, & Meyer, 1999). Note that the practiced and unpracticed number words were combined with the presentation of old and new auditory information (i.e., sine-wave and square-wave tones). We combined manipulations of both perceptual and response information in order to assess the separate and, in addition, the mutual effects of stage shortening of processes located at the perception and motor stages.

If changes of the specific timbre and number words were to result in prolonged RTs, this would point, respectively, to shortening of timbre information processing at the perception stage and/or to shortening of verbal response execution at the motor stage (see Pashler & Baylis, 1991). In contrast, if RTs were to remain constant after, relative to before, the changes of wave forms (i.e., timbre) and number words, then potential changes in the time to execute the associated processes would not significantly contribute to reductions of the overall task-processing time. Note that constant RTs after introducing manipulated information would not rule out the possibility of other explanations for why processing time could be reduced after practice. For example, such a finding might also be consistent with the assumption that practice effects could influence the perceptual categorization of the auditory stimuli. We will return to that issue in the General Discussion section.

Method

Participants

Eight participants (mean age: 24.0 years; four female, four male) took part in this experiment. They were paid for their participation at a rate of €8 per session, plus performance-based bonuses (for details, see the Procedure section). All participants were right-handed, native German speakers, had normal or corrected-to-normal vision, and were naïve to the purpose of the experiment.

Apparatus and component tasks

The experiment was carried out on a Pentium 1 PC and controlled by the Experimental Runtime System software (ERTS; Beringer, 2000). In the visual task, participants responded manually to a white circle at a left, central, or right position. These positions were horizontally arranged on the black background of a computer screen. The stimulus subtended approximately 2.38° of visual angle, and the possible positions were separated by approximately 0.95° of visual angle at a viewing distance of 60 cm. Three white dashes that served as placeholders for the possible positions were placed approximately 0.5° below the stimuli on the screen. They appeared as a warning signal 500 ms before the imperative stimulus was presented. The stimulus remained visible until the participant responded or until a 2,000-ms response interval had expired. Participants responded manually by pressing a spatially compatible response button with the index, middle, or ring finger of their right hand, according to the location of the stimulus on the computer screen. The task conditions of the visual task remained constant throughout the entire experiment.

In the auditory task, participants responded vocally to tones presented by headphones. Sine-wave tones were presented to one half, and square-wave tones to the other half of the participants during the practice sessions. The tones lasted 40 ms and were 350, 900, or 1650 Hz in frequency. Half of the participants responded by saying "one," "two," or "three" to the low-, middle-, and high-pitched tones, respectively, during all practice sessions. The remaining participants responded with "eleven," "twelve," or "thirteen" to the tones of different pitches during these sessions.[1] The stimulus and response conditions of the auditory task were equally balanced between participants. To acquire an accurate measurement of vocal RTs, participants' vocalizations were recorded with a microphone and a voice key, also connected to the experimental computer. The experimenter typed the actual response on a computer keyboard so that accuracy could be assessed in the analysis. As in the visual task, three dashes were presented at the same positions 500 ms before tone onset and remained visible until the participant responded or until a 2,000-ms response interval had expired.

In Sessions 9 and 10, old and new tones were intermixed. That is, we presented sine-wave and square-wave tones to all of the participants. During Session 9, participants were instructed to respond with the old, practiced number words. The participants were instructed to respond with the new, unpracticed number words during Session 10. Thus, the participants who had practiced the number words "one,"

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[1] Prior testing had shown that these triplets of number words revealed similar patterns of response latencies ("one"–"two"–"three" = 649 ms vs. "eleven"–"twelve"–"thirteen" = 675 ms, $p > .42$). That is, we found no significant differences between the latencies of "one" and "eleven" ("one" = 616 ms vs. "eleven" = 654 ms, $p > .15$), "two" and "twelve" ("two" = 715 ms vs. "twelve" = 739 ms, $p > .53$), and "three" and "thirteen" ("three" = 645 ms vs. "thirteen" = 632 ms, $p > .68$).

"two," and "three" changed to "eleven," "twelve," and "thirteen," and vice versa.

Feedback was given after each trial. In particular, after each trial the actual RT was presented for 1,500 ms when a correct answer was given. When both tasks were performed in one trial, the RT of the faster response was presented. When participants produced an incorrect response or omitted their response, the word *error* appeared at the center of the screen.

Procedure

Across the ten sessions, participants performed two types of trial blocks. In single-task blocks, they performed 48 trials (Sessions 9 and 10) or 45 trials (all remaining sessions) of either the visual or the auditory task. The order of the stimuli in a single-task block was randomized, and the stimuli appeared equally often. In the mixed blocks of Sessions 9 and 10, 18 dual-task trials were mixed with 24 single-task trials (12 trials with the visual task and 12 with the auditory task) in Sessions 9 and 10, while these dual-task trials were mixed with 30 single-task trials (15 trials with the visual task and 15 trials with the auditory task) in the remaining sessions. The single-task trials (in mixed blocks) helped to ensure that participants were equally prepared for both tasks in dual-task trials. In the dual-task trials, we presented a visual and an auditory stimulus simultaneously. Participants were instructed to respond to the visual and the auditory stimulus as quickly and accurately as possible. Within a mixed block, the order of single- and dual-task trials was randomized and stimuli appeared equally frequently; in Sessions 9 and 10, the numbers of presentations of old and new auditory stimuli were also equally balanced within blocks.

In Session 1, participants were presented with six single-task blocks of each task type, in alternating order. The initial task block was counterbalanced across participants. Sessions 2 to 8 proceeded as follows: Participants started with two single-task blocks (one of each task type), followed by 14 blocks consisting of four single-task blocks (two of each task type) and ten mixed blocks (in Session 2, only eight mixed blocks). Except for the initial two blocks, the single-task blocks were alternating and separated by two mixed blocks. The procedure of Sessions 9 and 10 was similar, except that 19 blocks followed the two initial blocks. Here, six single-task and 13 mixed blocks followed, with the same scheme of block order as during the practice sessions.

As in the Schumacher et al. (2001) study, participants were not told to respond in any particular order, and were told that they should give equal priority to the two tasks. The instructions were designed to encourage participants to perform the tasks as quickly and accurately as possible in all trials and blocks.

As in Schumacher et al. (2001), a payment scheme was introduced in order to boost fast and accurate performance. However, we introduced some changes to the payment scheme. Unlike in the Schumacher et al. study, separate target times were computed for the single-task and dual-task trials. Furthermore, the target times of the single-task trials were computed only from the single task in single-task blocks (see Tombu & Jolicœur, 2004). The single-task trials in the mixed blocks were excluded from the bonus payment system. Target times for the dual-task trials were computed from the dual-tasks trials in the mixed blocks. Participants received bonuses for both the single-task and mixed blocks on the basis of the respective criteria, and response errors were penalized. To ensure that participants continually responded as quickly as possible, the target times were reduced whenever the mean target time for the current block was lower than the best target time in any preceding block of the same type. Both the current target time and the best target time were presented after each block to the participants.

Results

For the analyses of practice effects, we included single-task trials (from single-task blocks), mixed single-task trials (from mixed blocks), and dual-task trials. For the analyses of transfer effects, we focused on (1) single-task trials in single-task blocks and (2) dual-task trials. Single-task trials in mixed blocks were excluded from the analysis because these trials (1) do not enable a "fair" analysis of dual-task costs (Strobach, Frensch, Soutschek, & Schubert, 2012; Tombu & Jolicœur, 2004) and (2) do not relate to the specific issue of stage shortening in the "pure" single-task conditions; note that a mixed single task includes processes of task activation and increased working memory load due to preparation for the two potential component tasks presented in mixed blocks. The latter aspects might not allow for a systematic investigation of stage shortening in a task performed in isolation (i.e., a single task in single-task blocks). For the error analysis, we included only trials in which a minimum of one response was incorrect (see, e.g., Bherer et al., 2005, 2008; Herath, Klingberg, Young, Amunts, & Roland, 2001; Logan & Schulkind, 2000). The error analysis of the practice sessions (Sessions 2–8) revealed error rates of 3.5 % for the visual task and 6.5 % for the auditory task in the single-task trials. The dual-task trials (Sessions 2–8) showed an error rate of 8.9 %. In each part of the Results section, including the transfer analyses, the data of the manipulated auditory task are presented first, while the data of the nonmanipulated visual task are presented second. RTs (for correctly performed trials) during practice are displayed in Fig. 1, and RT and error data from during practice and the manipulated conditions are displayed in Table 2. Session 1 was devoted to helping

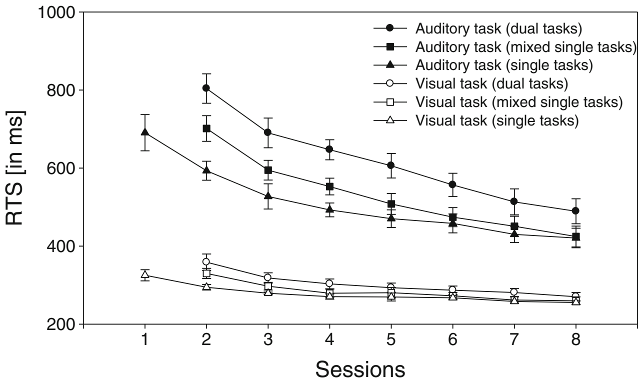

Fig. 1 Reaction times (RTs, for correctly performed trials only) in single task (i.e., single task in single-task blocks), mixed single task (i.e., single task in mixed blocks), and dual task of the visual and auditory tasks in Experiment 1's Practice Sessions 1 to 8. Session 1 was the introductory session, and its data were not included in the practice analyses. *Error bars* indicate standard errors

participants get acquainted with the materials, and data from that session thus were not included in our statistical analyses.

Dual-task practice (Sessions 2–8)

The practice results demonstrated improved component-task processing in the single and the dual tasks (see also Hazeltine et al., 2002; Liepelt, Fischer, Frensch, & Schubert, 2011; Schumacher et al., 2001; Strobach, Frensch, & Schubert, 2008; Tombu & Jolicœur, 2004). Importantly, this improvement was accompanied by greater RT shortening in the auditory-and-visual dual task than in single tasks; consequently, this led to a practice-related reduction of the dual-task RT costs (i.e., the difference between RTs in dual-task trials and in single-task trials from the single-task blocks) from 185 ms, $t(7) = 5.602$, $p < .001$, to 60 ms, $t(7) = 2.723$, $p < .05$, in the auditory task, and from 83 ms, $t(7) = 3.653$, $p < .01$, to 20 ms, $t(7) = 2.832$, $p < .05$, in the visual task.

Transfer effects

Auditory task To examine possible practice-related changes in the processing times of the perception and motor stages in

Table 2 Mean reaction times (for correctly performed trials) and mean error rates (in parentheses) for the auditory and visual tasks by session (1–10) and trial type (single task [in single-task blocks only], mixed single task [in mixed blocks], and dual task) in Experiment 1

	Old Stimuli			New Stimuli		
Sessions	Single Task	Mixed Single Task	Dual Task	Single Task	Mixed Single Task	Dual Task
Auditory Task						
1	690 (10.3)	–	–	–	–	–
2	590 (4.7)	701 (8.7)	775 (8.5)	–	–	–
3	520 (4.4)	595 (5.9)	665 (7.5)	–	–	–
4	477 (4.9)	553 (6.1)	622 (6.2)	–	–	–
5	456 (5.1)	508 (7.0)	578 (6.5)	–	–	–
6	445 (5.8)	474 (8.4)	532 (5.9)	–	–	–
7	419 (6.7)	451 (5.7)	491 (5.9)	–	–	–
8	405 (6.9)	425 (7.3)	465 (4.8)	–	–	–
9*	519 (11.1)	514 (13.5)	554 (10.6)	545 (19.3)	534 (14.4)	582 (15.4)
10**	507 (12.9)	504 (15.5)	553 (11.7)	518 (18.4)	522 (20.2)	578 (16.3)
Visual Task						
1	317 (1.3)	–	–	–	–	–
2	289 (1.7)	330 (0.7)	372 (8.5)	–	–	–
3	276 (2.7)	297 (0.9)	321 (7.5)	–	–	–
4	268 (3.2)	279 (1.7)	307 (6.2)	–	–	–
5	265 (3.7)	281 (1.4)	299 (6.5)	–	–	–
6	263 (3.5)	273 (2.1)	291 (5.9)	–	–	–
7	256 (3.9)	262 (2.8)	282 (5.9)	–	–	–
8	253 (4.1)	260 (2.5)	273 (4.8)	–	–	–
9*	253 (4.0)	265 (2.0)	279 (10.6)	–	256 (2.4)	278 (15.4)
10**	247 (3.9)	256 (2.4)	278 (11.7)	–	279 (1.1)	275 (16.3)

Sessions 2 to 8 represent the practice sessions, and processes at the input and output stages were manipulated in Sessions 9 and 10 (manipulation tests). Session 1 was the introductory session, and its data were not included in the practice analyses. * Old responses in manipulation test. ** New responses in manipulation test the auditory task, we analyzed the data from Sessions 9 and 10. We conducted 2 × 2 × 2 repeated measures analyses of variance (ANOVAs) with the factors Stimulus (old vs. new stimuli), Response (old responses [Session 9] vs. new responses [Session 10]), and Trial Type (single vs. dual task) on RTs and error rates. The detailed RT data of the manipulated auditory task are illustrated in Fig. 2.

The RT analysis of the auditory task revealed an effect of stimulus, $F(1, 7) = 6.447$, $p < .05$, $\eta_p^2 = .48$, which reflects the fact that RTs were shorter for trials with old than for trials with new stimuli in the transfer sessions. In contrast, changes of the required motor responses (i.e., transfer from old to new number words) produced no significant effect on the RTs in either the single-task or dual-task trials. The interaction between stimulus and response was not significant, and we found no effect of or interactions with the factor Trial Type.

As is illustrated in Fig. 2, the introduction of new auditory information in Session 9 resulted in increased auditory-task RTs for dual-task trials, and at the same time reduced the amount of dual-task costs [i.e., dual-task RTs minus single-task RTs; for Session 8 vs. Session 9, $t(7) = 2.546$, $p < .05$]. The latter result reveals that the manipulation of auditory information led to a larger increase of the auditory RTs in single-task contexts ($M = 114$ ms), $t(7) = 3.923$, $p < .01$, than in dual-task contexts ($M = 89$ ms), $t(7) = 3.175$, $p < .01$.

The error analysis of transfer effects in the auditory task showed a significantly increased error rate with new as compared to old auditory stimuli, $F(1, 7) = 7.802$, $p < .05$, $\eta_p^2 = .53$. All other main effects and interactions were nonsignificant.

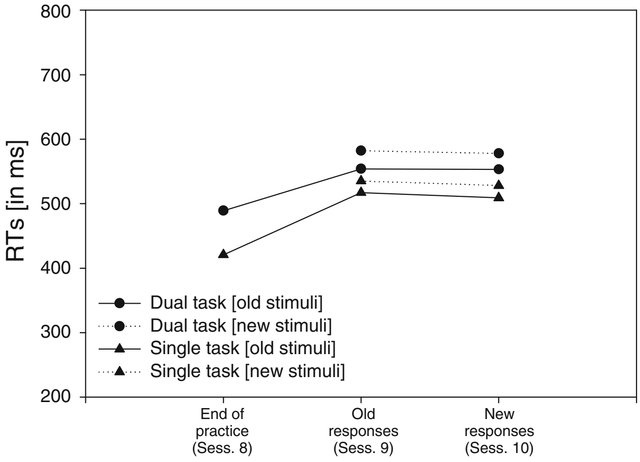

Fig. 2 Details of the reaction times (RTs, in milliseconds) before and after manipulations in the auditory task in Sessions 9 (old responses) and 10 (new responses) in Experiment 1. In Sessions 9 and 10, new auditory stimuli (*dotted lines*) were presented intermingled with the old stimuli (*solid lines*). In Session 10, a new verbal motor response was required instead of the old verbal responses practiced before. Single- and dual-task data at the end of practice are included from Session 8. Sess = Session

Visual task To analyze the dual-task performance in the visual task, we entered the data of the dual-task trials in Sessions 9 and 10 into repeated measures ANOVAs with the factors Stimulus (old vs. new auditory stimuli) and Response (old vs. new vocal response in the auditory task). The RT and the error data showed neither main effects nor interactions. Thus, we found no effect of the auditory-task manipulation on participants` performance in the visual dual-task trials.

Discussion

For the auditory task, the introduction of new timbre information led to increased RTs, relative to the situation with old stimulus information. This finding is consistent with the assumption that the time needed to process the specific timbre information at the perception stage of the auditory task had been reduced as a result of practice. As a second main finding, the introduction of new task information at the motor stage revealed an increase of RTs in neither the single-task nor the dual-task trials, suggesting that changes in the time to execute the verbal motor responses were not a primary factor contributing to the practice-related changes in the overall RTs in the auditory task. Potentially, some learning could occur with new stimuli within Session 9 and/or between Sessions 9 and 10 (e.g., due to effects of consolidation), which might have compensated for a potential prolongation of RTs from Session 9 to Session 10 after we introduced new motor information. Such compensation might have confounded our present conclusions on shortening at the motor stage. We assume, however, that the effect size of learning within a single session/between two sessions would be relatively small in comparison to the effect size due to learning during and between the previous Practice Sessions 1–8, and thus should present only a small confound in our conclusions on motor-stage shortening.

The introduction of new stimuli in Session 9 resulted in a greater RT increase in the single task than in the dual task (when contrasted with RTs in Session 8), leading to a reduction of dual-task costs. This asymmetric effect may have occurred because the auditory task was processed second in the dual-task context, and an emerging bottleneck may have led to the occurrence of a slack time in the processing stream of that task; in this case, part of the increased processing time in the auditory perception stages might have been absorbed by this slack time (Pashler, 1994). Nevertheless, we assume that any absorbed processing time should have similar effects on the performance in trials with old and new auditory stimuli during Sessions 9 and 10 and should not obscure an adequate comparison between the processing of both types of stimuli. We assume that an alternative explanation, that the asymmetric RT increase in the auditory dual task versus the single task and the accompanying decrease in dual-task costs are due to strategic changes in the amount of parallel processing (Meyer & Kieras, 1997), is not plausible. This is because, if the introduction of new task information (e.g., new auditory stimuli) resulted in changes in the dual-task processing strategy at all, it would theoretically change dual-task processing toward a more cautious processing strategy, leading to a reduction in the amount of parallel task processing and an increase of dual-task costs. The present data, however, show the opposite effect (i.e., decreased costs).

Experiment 2

In Experiment 2, we tested a new group of participants, who practiced the dual-task and single-task trials as in Experiment 1 for eight practice sessions (see Table 1). We applied manipulations of the visual task in transfer sessions after practice in order to test for possible practice-related shortening of perception and motor stages in the visual task.

In Sessions 9 and 10, we intermixed old (e.g., circles) and new (e.g., triangles) visual stimuli in order to detect a possible practice-related speed-up of processes involved in form identification at the perception stage. The old and new visual stimuli differed only with regard to form, but not in the remaining dimensions (e.g., position, size, color, or contrast); therefore, new visual stimuli belonged to the same task-relevant categories of old visual stimuli at left, central, and right positions (Pashler & Baylis, 1991). In line with Ahissar and Hochstein (1993), we selected the form information for manipulation because this type of information is processed early in the task-processing stream (Julesz, 1990). Thus, form information should be processed at the perception stage, but not at later stages such as the response-selection stage.

Furthermore, we changed the manual responses from Session 9 to Session 10 in order to assess learning at the motor stage. As in Pashler and Baylis (1991), participants practiced with the index, middle, and ring fingers of their right hand and shifted to the ring, middle, and index fingers of the left hand, and vice versa. The spatial compatibility of the stimuli to the motor responses was thus held constant. Due to the introduction of the new motor response information, we could assess possible practice-related shortening at the level of the specific motor effectors. Note that this manipulation does not test for a shortening of processing times at higher-order hierarchical motor programs that are associated with processing of some abstract structure of the motor programs (Schmidt, 1975). Practiced and unpracticed finger responses were combined with the presentation of the old and new visual stimuli. We combined manipulations of both perceptual and response information in order to assess the separate, but also the mutual, effects of potential stage shortening of processes located at the perception and motor stages.

If changes of the specific stimulus form and of the response fingers were to lead to RT increases, this would point to practice-related shortenings of the following types: identification of the specific form information, at the perception stage, or manual motor command execution, at the motor stage, respectively. In contrast, no conclusive evidence for specific shortening of a process would emerge if RTs were to remain constant after, relative to before, the corresponding transfer manipulation.

Method

Participants

Eight participants (mean age, 26.8 years; four females, four males) performed eight practice sessions and two transfer sessions, 9 and 10. They were paid for their participation at a rate of €8 per session, plus performance-based bonuses (for details, see the Procedure section). All of the participants were right-handed, native German speakers, had normal or corrected-to-normal vision, and were naïve to the purpose of the experiment.

Apparatus, stimuli, and procedure

These were similar to the relevant aspects of Experiment 1, with the following exceptions. Half of the participants practiced the visual task with their right hand, and the remaining participants with their left hand during the eight practice sessions. Furthermore, sine-wave tones were presented, and all participants responded with the verbal answers “one,” “two,” and “three” in the auditory task.

The manipulations of the visual task in Sessions 9 and 10 were as follows. In these sessions, we intermixed the presentation of old visual stimuli (i.e., circles) with new visual stimuli (i.e., triangles) in the visual task and instructed participants to respond according to the position of the two types of stimuli. Participants responded with the practiced hand during Session 9. During Session 10, they responded with the unpracticed hand.

Note that we cleanly flip the assignment of the response sets from practice to transfer; this clean flip had also been realized for each set of stimuli and responses in Experiment 1. However, this was not the case for the visual stimulus information, because all participants practiced with circles and were transferred to triangles in the present experiment. This method of stimulus manipulation could potentially confound the present conclusions, because of different baseline processing times for the circle and triangle forms. However, a control experiment demonstrated no single- versus dual-task RT difference between the circle and triangle versions of the visual task at low levels of practice—that is, in a second practice session. In the control experiment, the main effect of the factor Stimulus (old vs. new stimuli) and the interaction of this factor with trial type (single vs. dual tasks) were nonsignificant: $F(1, 17) = 1.214$, $p > .29$, and $F(1, 17) < 1$, respectively, in a repeated measures ANOVA on RTs. Thus, potential differences between the circle and triangle versions of the visual task during Sessions 9 and 10 could not be a result of different baseline processing times.

Results

The analyses of the data from Experiment 2 were identical to those performed for Experiment 1. The analysis of the error rates in Practice Sessions 1–8 revealed 2.1 % errors in the visual task and 3.7 % errors in the auditory task in single-task trials. The analysis of the dual-task trials (Sessions 2–8) revealed an overall error rate of 8.7 %. In the Results section, the data from the manipulated visual task are presented first, while the data from the not-manipulated auditory task are presented second. RTs (for correctly performed trials) during practice are displayed in Fig. 3, and the RT and error data from practice and transfer are displayed in Table 3. As in Experiment 1, Session 1 was devoted to helping participants get acquainted with the materials, and the data were thus not included in our statistical analyses.

Dual-task practice (Sessions 2–8)

The practice results resembled those from Experiment 1, with improved single- and dual-task processing in both component tasks. Importantly, this improvement resulted in a greater reduction of the visual and auditory dual-task RTs as compared to single-task RTs and, consequently, in a practice-related reduction of the dual-task RT costs from 124 ms, $t(7) = 3.122$, $p < .05$, to 15 ms, $t(7) = 2.517$, $p < .05$, in the visual task, and from 223 ms, $t(7) = 10.579$, $p < .001$, to 61 ms, $t(7) = 3.675$, $p < .01$, in the auditory task.

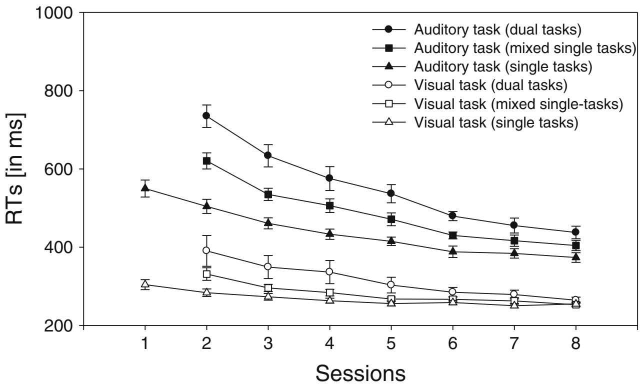

Fig. 3 Reaction times (RTs, for correctly performed trials only) in single task (i.e., single task in single-task blocks), mixed single task (i.e., single task in mixed blocks), and dual task of the visual and auditory tasks in Experiment 2's Practice Sessions 1 to 8. Session 1 was the introductory session, and its data were not included in the practice analyses. *Error bars* indicate standard errors

Transfer effects

Visual task We tested for possible practice-related changes in the processing times of the perception and motor stages in the visual task by analyzing the data from Sessions 9 and 10. As in Experiment 1, we conducted a 2 × 2 × 2 repeated measures ANOVA with the factors Stimulus (old vs. new stimuli), Response (old responses [Session 9] vs. new responses [Session 10]), and Trial Type (single vs. dual task). The detailed RT data from the manipulated visual task are illustrated in Fig. 4.

The RT analysis of the visual task revealed an effect of response, $F(1, 7) = 10.123$, $p < .05$, $\eta_p^2 = .59$: RTs were increased in contexts with new motor responses (with the unpracticed hand) as compared to RTs with the old motor responses (with the practiced hand). However, the factor Response was separately modulated by the Trial Type and Stimulus factors, suggesting that the effect of changing the response hand was modulated both by the demands of the task (i.e., single vs. dual) and by the novelty of the stimuli. In detail, the significant interaction between response and trial type for RTs, $F(1, 7) = 8.617$, $p < .05$, $\eta_p^2 = .55$, reflects the fact that RTs increased from contexts with old responses to contexts with new responses only for the single-task trials, $F(1, 7) = 14.047$, $p < .01$, $\eta_p^2 = .67$, and not for dual-task trials, $F(1, 7) < 1$. Furthermore, the interaction between response and stimulus was marginally significant, $F(1, 7) = 5.186$, $p < .06$, $\eta_p^2 = .43$. This marginal interaction reflects the finding that the change of the response hand from Session 9 (old responses) to Session 10 (new responses) led to significantly increased RTs only for the old visual stimuli, $F(1, 7) = 13.463$, $p < .01$, $\eta_p^2 = .66$, but not for the new visual stimuli, $F(1, 7) = 4.337$, $p > .08$, $\eta_p^2 = .33$. The effect of the Stimulus factor was nonsignificant, $F(1, 7) < 1$, indicating similar RTs in the conditions with old and new visual stimuli. The main effect of trial type and the other interactions were nonsignificant. The corresponding error analysis revealed no significant effects or interactions.

Auditory task The dual-task RTs in the auditory task were analyzed in a repeated measures ANOVA with the factors Stimulus (old vs. new visual stimuli) and Response (old vs. new responses). This analysis showed an effect of response, $F(1, 7) = 7.516$, $p < .05$, $\eta_p^2 = .52$, indicating a significant increase in RTs from conditions with old to those with new responses. The effect of stimulus and the combination of both factors were nonsignificant.

Table 3 Mean reaction times (RTs for correctly performed trials) and mean error rates (in parentheses) for the visual and auditory tasks by session (1–10) and trial type (single task [in single-task blocks only], mixed single task [in mixed blocks], and dual task) in Experiment 2

	Old Stimuli			New Stimuli		
Sessions	Single Task	Mixed Single Task	Dual Task	Single Task	Mixed Single Task	Dual Task
Visual Task						
1	304 (1.1)	–	–	–	–	–
2	284 (1.5)	331 (1.0)	407 (8.8)	–	–	–
3	273 (1.8)	296 (0.7)	357 (5.3)	–	–	–
4	263 (1.6)	284 (0.8)	345 (5.1)	–	–	–
5	256 (2.5)	268 (0.7)	309 (5.4)	–	–	–
6	259 (2.9)	267 (1.1)	293 (4.8)	–	–	–
7	250 (3.7)	263 (1.3)	291 (7.3)	–	–	–
8	255 (2.4)	253 (1.4)	271 (5.4)	–	–	–
9*	238 (3.5)	247 (2.6)	258 (6.0)	242 (3.4)	253 (0.7)	262 (4.8)
10**	264 (3.7)	254 (3.7)	262 (6.6)	257 (2.7)	260 (1.6)	262 (5.0)
Auditory Task						
1	550 (7.3)	–	–	–	–	–
2	504 (2.7)	621 (6.1)	727 (8.8)	–	–	–
3	461 (2.4)	535 (4.7)	628 (5.3)	–	–	–
4	433 (2.3)	506 (4.7)	571 (5.1)	–	–	–
5	415 (2.6)	471 (4.3)	532 (5.4)	–	–	–
6	388 (2.7)	430 (5.3)	472 (4.8)	–	–	–
7	384 (4.4)	417 (6.1)	452 (7.3)	–	–	–
8	374 (3.1)	404 (5.3)	435 (5.4)	–	–	–
9*	367 (3.5)	394 (6.1)	424 (6.0)	–	394 (6.1)	422 (4.8)
10**	355 (3.3)	382 (5.5)	403 (6.6)	–	382 (5.5)	399 (5.0)

Sessions 2 to 8 represent the practice sessions, and processes at the input and output stages were manipulated in Sessions 9 and 10 (manipulation tests). Session 1 was the introductory session, and its data were not included in the practice analyses. *Old responses in manipulation test. **New responses in manipulation test

The identical error rate analysis showed a main effect of stimulus, $F(1, 7) = 11.929$, $p < .05$, $\eta_p^2 = .63$. We found fewer errors in dual-task trials that had new stimuli in the visual task ($M = 4.3$ %) than in the dual-task trials that had old stimuli in the visual task ($M = 5.6$ %); this finding may be explained by a reduced degree of attentiveness in the practiced dual task (i.e., with old visual stimuli) as compared with the unpracticed dual task (i.e., with new visual stimuli), due to reduced processing demands in the former dual-task type (Hazeltine et al., 2002). The effects of response and of the combination of response and stimulus were not significant. Thus, the manipulation of the visual task did not result in impaired auditory-task processing.

Discussion

For the perception stage, the lack of a main effect of the new stimuli on RTs is consistent with the hypothesis that, if it occurred, a possible shortening of the processes in identifying the visual stimulus form did not contribute to the overall practice-related shortening in the visual task. The transfer manipulation of the response hand did not affect performance in the dual-task trials, which is consistent with the dual-task findings from the auditory task, although the response modalities were different in Experiment 1 (verbal) and Experiment 2 (manual). As in Experiment 1, there could have been some learning with new visual stimuli within Session 9 and/or some learning between Sessions 9 and 10 (e.g., due to effects of consolidation), which might have compensated for a potential prolongation of RTs from Session 9 to Session 10 after we introduced the new motor information. Such compensation might have confounded our present conclusions on shortening at the motor stage. We assume, however, that the size of this learning effect within a single session or between two sessions should be relatively small in comparison to the effect size due to learning during and between the previous Practice Sessions 1 to 8, and thus should present only a small confound for our conclusions on motor-stage shortening.

For single-task trials, we found an effect of the response hand on RTs, which indicated that practice led to a possible shortening

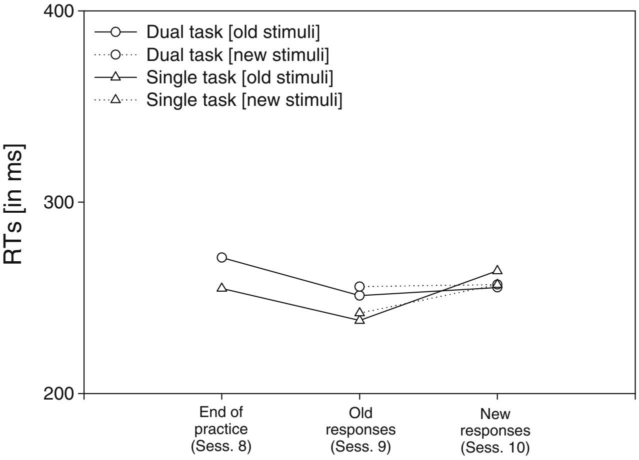

Fig. 4 Details of the relevant reaction times (RTs, in milliseconds) before and after manipulations of the visual task in Sessions 9 (old responses) and 10 (new responses) in Experiment 2. In Sessions 9 and 10, new visual stimuli (*dotted lines*) were presented intermingled with the old stimuli (*solid lines*). In Session 10, a new manual motor response was required instead of the old manual responses that had been practiced before. Single- and dual-task data at the end of practice are included from Session 8. Sess = Session

of the processing routines involved in the execution of the manual responses. This contributed to the overall practice-related RT reduction only in single-task trials, but not in dual-task trials. A further specification of the effect of the response hand is given by the fact that the prolongation of the visual-task RTs was found in contexts with old but not with new visual stimuli. This suggests that the shortened motor response routines were specifically associated with the old stimuli, but not with the new stimuli (Pashler & Baylis, 1991). After changing the required motor response, the old visual stimuli were associated with the wrong motor responses, which led to additional processing time when executing the response.

Experiment 3

In Experiment 3, we tested a new group of participants who practiced dual-task and single-task trials for eight practice sessions. Following this, we applied manipulations of the response-selection information (i.e., stimulus–response mapping rules) of the visual and auditory tasks in Transfer Session 9 in order to test for possible practice-related shortening at the central response-selection stages in these tasks.

To test for central-stage shortening, the stimulus–response mapping rules given during practice in both the visual and auditory tasks of the present experiment required a change when compared with the specific characteristics of these rules in the original version of Schumacher et al. (2001), as well as the present Experiments 1 and 2. This is because the compatible mappings between visual stimuli and manual keypress responses and between tone pitches and number words in these prior experiments were relatively easy and simple (Kornblum, Hasbroucq, & Osman, 1990; Ruthruff et al., 2006). After testing these rules, it was critical to create an alternative set of mapping rules between the visual stimuli and manual responses, *and* between the tone stimuli and verbal responses, of comparable levels of difficulty and complexity. This was required when introducing the new sets of mapping rules after practice, to firmly assess the impact of this introduction of new rules on single- and dual-task processing times—that is, to test for potential shortening at the central-stage level. If mapping rules of different difficulty and complexity levels were applied during practice and transfer, a task context could be introduced with different baseline processing times; in this case, potential changes in RTs after the introduction of the new mapping rules during transfer could not be interpreted as indicators of central-stage shortening during prior practice.

To meet these requirements of two sets of mapping rules in the visual and auditory tasks with comparable levels of difficulty and complexity (resulting in similar baseline processing times), we introduced (among other changes) two mayor changes into the practice and transfer phases of Experiment 3, in contrast to Experiments 1 and 2: (1) Participants practiced incompatible sets of stimulus response mapping rules in the auditory and visual tasks (e.g., left, central, and right circle positions were incompatibly mapped onto middle-, index-, and ring-finger buttonpresses, respectively) and were then transferred to a context with an alternative, incompatible set in either the auditory or the visual task (e.g., the left, central, and right circle positions could be mapped onto index-, ring-, and middle-finger buttonpresses, respectively); (2) participants performed initial test phases with both the incompatible practice and transfer sets in the visual and auditory tasks at the beginning of practice. This initial test allowed us to control for similar levels of baseline performance with the mapping rule sets presented during practice and transfer, and to exclude confounds with differences between these levels that could affect performance in later transfer tests. While this initial baseline test was performed during Session 1, participants practiced one pair of sets of stimulus–response mapping rules in the following Sessions 2 to 8 and were then transferred to an alternative visual-task or auditory-task set in Session 9. An overview of the procedure of Experiment 3 is provided in Table 4. If changes of the specific stimulus–response mapping rules in the visual or the auditory task were to lead to RT increases in these tasks, this would point to practice-related shortening of processes at the central response-selection stages. In contrast, no evidence for a specific shortening of such processes would emerge if the RTs were to remain

Table 4 Overview of practice and transfer mapping conditions (see Methods section for details) across Sessions 1 to 9 in Experiment 3

Session	Description
Session 1	Practice and transfer stimulus–response mapping
Sessions 2–8	Practice stimulus–response mapping
Session 9	Transfer stimulus–response mapping

Half of the participants performed these mappings in the visual task (with a constant stimulus–response mapping in the auditory task), while the remaining participants performed these mappings in the auditory task (with a constant stimulus–response mapping in the visual task). Performance changes from Session 8 to Session 9 were analyzed in order to assess central-stage shortening

constant after, as compared to before, the corresponding transfer manipulation.

Method

Participants

A group of 12 participants (mean age 26.2 years; six females, six males) performed one baseline session (Session 1), followed by seven practice sessions (Sessions 2–8) and one transfer session (Session 9). As in previous experiments, they were paid for their participation at a rate of €8 per session, plus performance-based bonuses. All participants were right-handed, native German speakers, had normal or corrected-to-normal vision, and were naïve to the experiment's purpose.

Apparatus, stimuli, and procedure

These were similar to the respective aspects of Experiment 2, with the following exceptions. All participants performed the following stimulus–response mappings during Sessions 2 to 8: In the visual task, circles were presented at left, central, and right positions on the screen, and participants were instructed to respond manually by pressing a response button with the middle, index, and ring fingers of their right hand, respectively, according to the location of the stimulus. During these sessions, low-, middle-, and high-pitched sine-wave tones were presented, and all participants responded with the verbal answers "one," "three," and "two" in the auditory task, respectively. In the following transfer session (Session 9), the participants were transferred to a context that included manipulations of either the visual- or the auditory-task mapping rules (equally balanced between participants). Manipulations in the visual task resulted in the following mapping: left, central, and right circle positions were mapped onto buttonpresses with the index, ring, and middle fingers of the right hand. In the auditory-task transfer context, however, participants were instructed to give the number words "two," "one," and "three" for the low-, middle-, and high-pitched tones. In the former, visual-task transfer context, the auditory task remained constant, and in the latter, auditory-task transfer context, the visual task was not manipulated. The characteristics of the single-task and mixed blocks and the block order in Sessions 2 to 9 were identical to those aspects in Sessions 2 to 8 of Experiments 1 and 2. In contrast, Session 1 included two phases: Phase A included the set of stimulus–response mapping rules presented during practice, while Phase B included one of the sets of stimulus–response mapping rules presented during transfer; that is, half of the participants received different sets in the visual task, while the remaining participants performed different sets in the auditory task. Each phase started with six single-task blocks (three visual and three auditory, presented in alternating order), followed by four mixed blocks. The orders of Phases A and B in Session 1 were equally balanced between participants.

Results

The analysis of the error rates in Practice Sessions 1–8 revealed 3.5 % errors in the visual task and 6.0 % errors in the auditory task in the single-task blocks. The analysis of the dual-task trials (Sessions 1 to 8) revealed an overall error rate of 6.4 %. In the Results sections below, the data of the manipulated task are presented first and the data of the nonmanipulated task second. Session 1 was devoted to assessing baseline processing times of the tasks presented during practice and transfer, and its data were thus not included in our practice analyses.

Dual-task practice (Sessions 2–8)

As is illustrated in Fig. 5 and Table 5, the practice results of Sessions 2–8 demonstrated an improvement of component-task processing in the single and dual tasks; this trend was similar to what was found during practice in the original version of the Schumacher et al. (2001) task (e.g., in the present Exps. 1 and 2). Importantly, we found greater RT shortening in the visual-and-auditory dual task than in the single tasks; this greater shortening led to a practice-related reduction of the dual-task RT costs from 140 ms, $t(11) = 5.120$, $p < .001$, to 12 ms, $t(11) = 4.352$, $p < .001$, in the visual task, and from 295 ms, $t(11) = 10.174$, $p < .001$, to 91 ms, $t(11) = 4.823$, $p < .001$, in the auditory task.

Transfer effects

Manipulation of visual task

Visual task We tested for possible practice-related changes in the processing times of the central stage in the visual task

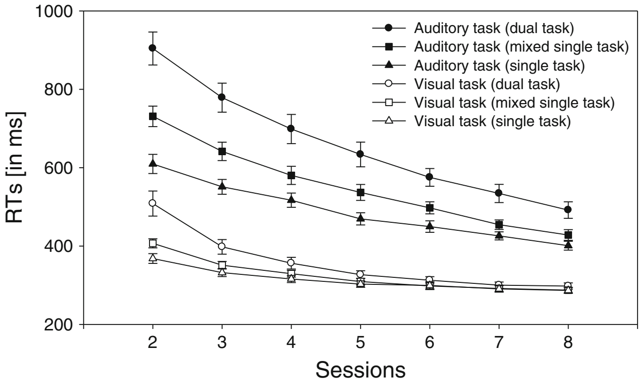

Fig. 5 Reaction times (RTs, for correctly performed trials only) in single task (i.e., single task in single-task blocks), mixed single task (i.e., single task in mixed blocks), and dual task of the visual and auditory tasks in Experiment 3's Practice Sessions 2 to 8, averaged across all participants. *Error bars* indicate standard errors

by analyzing the data (only correct responses in the RT analysis) from Sessions 8 and 9. We conducted 2 × 2 repeated measures ANOVAs with the factors Mapping Set (practice mapping set [Session 8] vs. transfer mapping set [Session 9]) and Trial Type (single task vs. dual task). The detailed RT data of the manipulated visual task are illustrated in Fig. 6 (left side).

The RT analysis revealed an effect of mapping set, $F(1, 5) = 70.117, p < .001, \eta_p^2 = .93$. RTs were increased in contexts with the transfer set (i.e., Session 9) as compared to RTs in contexts with the practice set (i.e., Session 8). This increase was modulated by trial type, $F(1, 5) = 13.728$, $p < .05$, $\eta_p^2 = .73$, reflecting a higher RT increase in the dual task ($M = 115$ ms), $t(5) = 8.923$, $p < .001$, than in the single task ($M = 80$ ms), $t(5) = 6.528$, $p < .001$. The main RT effect of trial type demonstrated a general single-task versus dual-task difference, $F(1, 5) = 10.236$, $p < .05$, $\eta_p^2 = .67$. The identical error rate analysis also showed a main effect of trial type, $F(1, 5) = 12.461$, $p < .05$, $\eta_p^2 = .71$, with higher error rates in the dual than in the single task, but no main effect of and interaction with mapping set, $Fs(1, 5) < 3.212$, $ps > .13$, η_p^2 s < .39. In sum, the present evidence of increased RTs in Session 9 versus Session 8 is consistent with the assumption of central-stage shortening in the visual task, with a tendency for increased shortening in dual-task contexts.

Comparisons of the baseline performance levels at the beginning of practice (i.e., in Session 1) demonstrated that the RT increase from Session 8 to Session 9 in the visual task showed no effect of differences in the initial processing times of the mapping sets presented during practice and transfer.[2] In detail, we analyzed the RT data of Session 1 in a repeated measures ANOVA including the factors Phase (Phase A, the practice mapping set, vs. Phase B, the transfer mapping set) and Trial Type (single vs. dual task). This analysis revealed a general single-versus-dual-task difference, $F(1, 5) = 30.792$, $p < .01$, $\eta_p^2 = .86$. Importantly, however, no main effect of and interaction with phase was evident, $Fs(1, 5) < 1$, demonstrating similar initial difficulty levels (i.e., similar RTs) of practice and transfer mapping sets.

An alternative assumption to explain the “general” RT increase in the visual task between Sessions 8 and 9 could be that additional inhibitory effects were required in order to deactivate the highly automatized mapping rules of the practice set before the transfer rules could be activated in Session 9 (Mayr, 2007). Such additional inhibition would be time consuming and slow down visual task processing. According to this assumption, the general RT increase from Session 8 to Session 9 would not result from the change from a practiced (i.e., shortened) to an unpracticed (i.e., unshortened) set of mapping rules, but from additional processes in the latter session (e.g., the initial activation of the practice mapping rules required inhibitory processes before the newly introduced rules could be initiated). We assume, however, that if such processes affected Session 9 performance, they would particularly affect visual-task performance during early transfer (i.e., at the beginning of Session 9) but would be negligible during later transfer (i.e., at the end of Session 9) after intense familiarization with the transfer set of mapping rules, when no inhibition of the practice set would be required. To analyze this “late” performance, we compared single- and dual-task visual RTs on the last (visual) single-task block and on dual-task trials of the last two mixed blocks of Session 8 (practice mapping set) and Session 9 (transfer mapping set). Similar performance levels in these blocks of the two sessions would be consistent with the assumption that inhibitory processes exclusively explain the general RT increase across sessions, while increased RTs in the Session 9 blocks would argue against an exclusive impact of such processes explaining the general RT increases. The analysis of the visual-task data demonstrated similar RT increases in the single and dual tasks from Session 8 to Session 9, $F(1, 5) = 42.187$, $p < .001$, $\eta_p^2 = .89$, which is consistent with the assumption that additional processes (e.g., inhibitory processes) do not exclusively explain the general RT increase between these sessions.

Auditory task The RT analysis of the auditory task in Sessions 8 and 9 showed generally higher RTs in the dual than in the single task, $F(1, 5) = 43.450, p < .001, \eta_p^2 = .90$, and an RT change from Session 8 to Session 9 (the latter session included a manipulation of the mapping set of the

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[2] In Session 1, the mean RTs (and standard errors) of the visual-task mapping sets presented during practice and transfer were, respectively, 484 (28) and 463 (28) ms in the single tasks, and 779 (76) and 767 (83) ms in the dual tasks.

Table 5 Mean reaction times (RTs for correctly performed trials) and mean error rates (in parentheses) for the visual and auditory tasks by session (2–9) and trial type (single task [in single-task blocks only], mixed single task [in mixed blocks], and dual task) in Experiment 3, separated into participant groups with manipulations of the mapping rules in the visual task (visual-task transfer) or in the auditory task (auditory-task transfer)

	Visual Task			Auditory Task		
Sessions	Single Task	Mixed Single Task	Dual Task	Single Task	Mixed Single Task	Dual Task
Visual-Task Transfer						
2	377 (1.4)	418 (3.3)	507 (14.0)	595 (6.6)	687 (8.3)	854 (14.0)
3	337 (1.9)	354 (2.7)	388 (7.1)	538 (6.1)	616 (5.1)	747 (7.1)
4	314 (2.2)	332 (2.3)	346 (5.6)	510 (3.3)	560 (3.7)	681 (5.6)
5	301 (3.8)	305 (2.3)	317 (6.9)	460 (6.4)	523 (4.4)	608 (6.9)
6	299 (4.1)	295 (3.2)	306 (7.0)	453 (5.1)	499 (4.9)	581 (7.0)
7	290 (4.0)	286 (3.3)	297 (6.1)	424 (4.4)	451 (7.1)	548 (6.1)
8	287 (4.0)	286 (3.9)	294 (9.4)	399 (6.0)	431 (5.9)	515 (9.4)
9	366 (5.0)	391 (6.4)	409 (14.4)	379 (6.9)	450 (4.9)	664 (14.4)
Auditory-Task Transfer						
2	359 (3.3)	396 (2.4)	510 (15.1)	624 (4.2)	775 (7.4)	954 (15.1)
3	327 (3.1)	348 (1.8)	408 (8.2)	564 (5.3)	667 (2.4)	810 (8.2)
4	317 (3.6)	327 (3.0)	367 (8.4)	523 (3.2)	600 (5.1)	717 (8.4)
5	305 (3.3)	314 (3.2)	337 (7.8)	479 (3.6)	551 (5.2)	659 (7.8)
6	300 (4.9)	301 (2.1)	319 (8.1)	447 (3.7)	496 (4.8)	569 (8.1)
7	291 (4.4)	297 (3.2)	304 (9.4)	428 (4.1)	457 (4.2)	520 (9.4)
8	287 (3.7)	289 (3.7)	303 (7.4)	403 (4.9)	426 (6.3)	468 (7.4)
9	287 (3.3)	302 (1.9)	367 (8.2)	592 (4.3)	662 (4.7)	767 (8.2)

Sessions 2 to 8 represent the practice sessions, and information at the central stages was manipulated in the transfer session (Session 9). Session 1 was the introductory session, and its data are not included

visual task), $F(1, 5) = 10.997$, $p < .05$, $\eta_p^2 = .69$. This RT change differed between the single and dual tasks, $F(1, 5) = 25.611$, $p < .01$, $\eta_p^2 = .84$; in fact, there was an RT increase in the dual task (in which both the manipulated visual task and the auditory task were combined), $t(5) = 4.173$, $p < .01$, but single-task RTs did not change across these sessions, $t(5) = 1.921$, $p > .15$. The error data showed no main effects or interactions, $F\text{s}(1, 5) < 4.165$, $p\text{s} > .09$, η_p^2 s = .45.

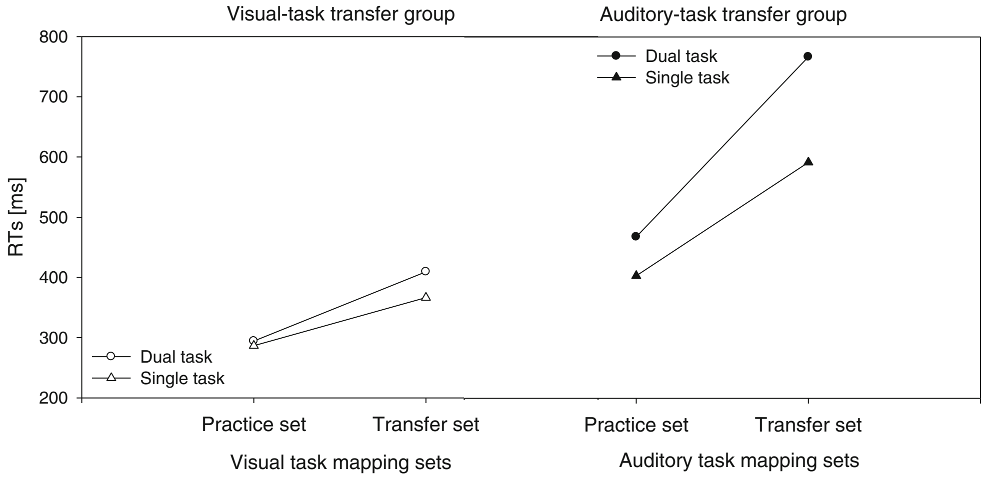

Fig. 6 Details of the relevant reaction times (RTs, in milliseconds) before and after manipulations of information at the central stage in the visual-task transfer group (*left side*) and the auditory-task transfer group (*right side*) from Session 8 (practice [visual task/auditory task] mapping set) to Session 9 (transfer [visual task/auditory task] mapping set). RTs are illustrated for single-task trials and dual-task trials. The Session 8 data (practice set) exclusively include data of the participants who were transferred to a new visual-task mapping (*left side*) or a new auditory-task mapping (*right side*)

Manipulation of auditory task

Auditory task We tested for possible practice-related changes in the processing times of the central stage in the auditory task with analyses identical to those we had used when testing for such shortening in the visual task (detailed RTs for the manipulated auditory task are illustrated in Fig. 6, right side). The RT analysis revealed an effect of mapping set, $F(1, 5) = 52.896$, $p < .001$, $\eta^2_p = .91$: RTs increased in trials with the transfer set (i.e., Session 9) relative to those in trials with the practice set (i.e., Session 8). This increase was modulated by the factor Trial Type, $F(1, 5) = 9.070$, $p < .05$, $\eta^2_p = .65$, reflecting a higher RT increase in the dual task ($M = 299$ ms), $t(5) = 5.838$, $p < .01$, than in the single task ($M = 188$ ms), $t(5) = 10.924$, $p < .001$. The main RT effect of trial type demonstrated a general single-versus-dual-task difference, $F(1, 5) = 13.871$, $p < .05$, $\eta^2_p = .74$. The error data supported this main effect of trial type, $F(1, 5) = 6.792$, $p < .05$, $\eta^2_p = .58$ (with higher error rates in the dual than in the single task), but showed no main effect of or interaction with mapping set, $Fs(1, 5) < 1$. In sum, the findings of increased RTs in Session 9 versus Session 8 are consistent with the assumption of central-stage shortening in the auditory task, with indicators for increased stage shortening in the dual-task context; the latter result is reflected by a higher RT increase in the dual relative to the single task.

Comparisons of the baseline performance levels at the beginning of practice (i.e., in Session 1) demonstrated that the RT increase from Session 8 to Session 9 in the auditory task was not an effect of differences in the initial processing times of the mapping sets presented during practice and transfer.[3] As with the visual-task transfer, we analyzed the RT data of Session 1 in a repeated measures ANOVA including the factors Phase (Phase A, with the practice mapping set, vs. Phase B, with the transfer mapping set) and Trial Type (single vs. dual task). This analysis revealed a general single-versus-dual-task difference, $F(1, 5) = 40.984$, $p < .001$, $\eta^2_p = .89$, but no main effect of and interaction with phase, $Fs(1, 5) < 1$, reflecting no difficulty difference between the practice and transfer mapping sets in the auditory task.

To rule out the alternative explanation that the RT increases from Session 8 to Session 9 could exclusively be due to, for instance, inhibitory effects (for the theoretical details, please refer to this section in the analysis of visual-task transfer), we tested single- and dual-task auditory RTs from the last (auditory) single-task block and from the dual-task trials of the last two mixed blocks of Session 8 (practice mapping set) and Session 9 (transfer mapping set). As in this analysis in the manipulated visual task, the auditory-task data demonstrated an RT increase from Session 8 to 9, $F(1, 5) = 28.798$, $p < .01$, $\eta^2_p = .85$ (but no difference between or interaction with the single and dual tasks), which is consistent with the assumption that inhibitory processes do not exclusively explain the general RT increase in all of the data from these sessions.

Visual task The RT analysis of the visual task in Sessions 8 and 9 showed generally higher RTs in the dual than in the single task, $F(1, 5) = 8.619$, $p < .05$, $\eta^2_p = .63$, but no other main effect or interaction, $Fs(1, 5) < 3.692$, $ps > .11$, $\eta^2_p s < .43$. The error data also showed a main effect of trial type, $F(1, 5) = 7.383$, $p < .05$, $\eta^2_p = .60$ (with higher error rates in the dual than in the single task), but no main effect of or interaction with mapping set, $Fs(1, 5) < 1$.

Discussion

The present experiment tested whether central-stage shortening contributes to increased efficiency in component-task processing and, as a result, to a reduction of dual-task costs with practice. These tests provided evidence for this assumption when investigating stage shortening in the visual and auditory tasks, which was the first direct evidence for response-selection stage shortening in a dual-task context. We mainly inferred this stage shortening from increased RTs after the introduction of a transfer set of stimulus–response mapping rules after practice in both the visual and auditory tasks. This introduction resulted in an increased effect in a dual versus a single task; we will come back to this difference in the General Discussion. The RT increase cannot easily be attributed to (1) different levels of initial baseline processing times of the practice and transfer mapping sets within both tasks or (2) an exclusive impact of inhibitory processes that were generated due to the introduction of the transfer mapping sets. Furthermore, the present experiment showed that practicing the dual-task context of Schumacher et al. (2001) as well as of the present Experiments 1 and 2 with incompatible mapping rules also leads to extreme improvements in dual-task performance. However, a moderate amount of dual-task costs remained at the end of practice in Session 8.

General discussion

Previous research had provided evidence for perfect time-sharing after extensive dual-task training combining an auditory and a visual component task (e.g., Hazeltine et al., 2002; Schumacher et al., 2001; Strobach, Liepelt, Schubert,

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[3] In Session 1, the mean RTs (and standard errors) of the auditory-task mapping sets presented during practice and transfer were, respectively, 439 (47) and 454 (55) ms in the single tasks, and 699 (94) and 738 (147) ms in the dual tasks.

& Kiesel, 2012; Tombu & Jolicœur, 2004). In the present study, we tested whether the accompanying practice-related processing changes related to specific stage shortenings of the perception, response-selection, and/or motor stages.

Effects of dual-task practice on central response-selection stages

Changes in stimulus–response mapping rules in the auditory and visual tasks led to significant impairments in performance (i.e., increased dual-task RTs) of these tasks in the transfer session of Experiment 3. This finding is consistent with the assumption that practicing rules for eight sessions shortens the processing routines at the central stage, which cannot be applied anymore in Session 9 (the transfer session). These results extend earlier findings on dual-task practice (Ruthruff et al., 2001, 2006; Sangals et al., 2007) that had suggested that a significant part of the speed-up is located on pre-motor stages. While a precise localization of the practice-related shortening specifically for the central stage had not been possible in these earlier studies, due to methodological constraints, the present transfer-based diagnostic method allowed for such a conclusion in our dual-task study. Even more importantly, we provided this evidence under conditions of optimal dual-task performance, which allowed us to reveal the whole potential of practice-related stage shortening in dual-task contexts (Hartley, Maquestiaux, & Silverman Butts, 2011).

Effects of dual-task practice on perceptual stages

For the perception stage, we found that the introduction of new timbre information in the auditory task affected the RTs of the participants in the dual-task trials of the transfer sessions (Exp. 1). The practiced routines involved in wave-form processing could not be applied anymore in the transfer session, and therefore participants' performance was impaired when processing new tone stimuli that differed in their wave-form information from the previously learned tone stimuli. Thus, in addition to the effects on the central stages, practice-related shortening in the identification of timbre information appears to be a second source of the speed-up in the auditory component task. This result, again, specifies the assumption of premotor-stage shortening in the component tasks used during dual-task practice by Ruthruff and colleagues (Ruthruff et al., 2001, 2006, Exp. 1) and indicates a further locus of the practice effect at the auditory perception stage. In addition, this finding extends the conclusions from previous single-task (Pashler & Baylis, 1991) and dual-task (e.g., Dux et al., 2009; Kamienkowski et al., 2011) practice studies, suggesting that practice is limited to the central response-selection stage only. This extension may be related to the tasks' input modalities, which differed between the previous single-task and dual-task practice studies (i.e., visual input modality) and the present Experiment 1 (i.e., auditory input modality).

This conclusion is in line with the results of our visual task. The results of the perception-stage manipulation did not show reliable changes in RTs when the form information of the visual stimuli was modified in dual-task trials (Exp. 2). These findings are consistent with the assumption that routines of visual-form processing did not speed up with practice, and may therefore not be related to the overall practice-related reduction in task contexts of the Schumacher et al. (2001) type. A potential reason for the discrepancy between the practice effects on the auditory and visual perception stages may be related to the different degrees of task relevance of the manipulated stimulus information. That is, while timbre information is more relevant for the auditory task (and its processing is shortened with practice), visual form information is less relevant (and shows no evidence for perception-stage shortening). An alternative reason for the discrepancy between the auditory and visual practice effects may be related to the different degrees of expertise with the underlying perceptual routines. While the wave-form discrimination of the tone frequencies used in the present study was rather unfamiliar to the participants, the perceptual routines for the visual identification of a circle seemed rather well practiced early in practice, potentially due to their ease of acquisition. The observed lack of RT changes when manipulating visual information does, however, not rule out the possibility of other explanations why the visual-task processing time might be reduced after practice. For example, such a finding is also consistent with the assumption that the perceptual categorization of the visual stimuli could also be influenced by practice effects.

Perhaps the use of more complex visual forms that required complex perception routines would lead to significant learning effects at the visual perception stage. This assumption is consistent with the findings of Ahissar and Hochstein (1993, 1997) and of Reingold, Charness, Pomplun, and Stampe (2001), demonstrating item-specific effects in visual perceptual learning with more complex visual stimuli than were used in the present study. Reingold et al., for example, demonstrated that chess masters showed evidence for a perceptual advantage in encoding complex stimuli, including potential chess positions, when compared with less-skilled chess players. Further studies will be required in order to assess the effects of stimulus complexity on possible sensory-stage shortening in single-task and dual-task learning. For dual-task processing, it seems to be essential to focus on task stimuli that enable near-perfect time-sharing with practice because, as we illustrated in the introduction, this type of performance may exclusively allow researchers to reveal the whole potential of practice-related perception stage shortening in dual-task contexts.

Effects of dual-task practice on motor stages

The present findings showed equal dual-task RTs before and after the manipulations of the motor stages. Equal performance indicated that the motor commands involved in response execution were not shortened during dual-task practice in the present task combination. For the findings of Schumacher et al. (2001) that showed perfect time-sharing, our results suggest that changes in motor execution seem not to be as important as the changes in perception and central response selection. While this is true for dual-task conditions (see also Kamienkowski et al., 2011; Ruthruff et al., 2001; Sangals et al., 2007), the situation is slightly different for practice in single-task trials. For single-task trials of the visual task, the manipulation of the response hand induced an increase in RTs in Session 10 (Exp. 2), probably because the practiced motor commands involved in manual response execution could not be applied anymore when transferred to the unpracticed hand. A shortening of the execution of manual motor responses seems to contribute to the practice-related reduction of processing time, at least in visual single-task trials. This finding seems at odd with the results of Pashler and Baylis (1991), who did not observe an effect of response hand on the RTs in an overall transfer analysis. One potential reason for this difference may be that Pashler and Baylis administered far fewer practice trials (n = 750 single-task trials) than we did in the present study (n = 1,965 single-task trials). This is also in line with the finding of a transient increase in RTs after a hand change in the very first transfer block after practice in the Pashler and Baylis study, indicating that the improved performance could not immediately be fully transferred to a new response hand.

The response hand effect in our study suggests that at least in single-task contexts, very simple motor execution processes, such as simple finger movements during keypresses, are enhanced, given a sufficient amount of practice. Additionally, the observation that the response hand effect was restricted to the single-task trials suggests that the need to control a second verbal motor response under dual-task conditions seemed to avoid such learning-related changes in the execution of simple manual responses. For the case of untrained dual-task contexts of the psychological refractory period type (e.g., Pashler, 1994), it has been shown that motor interference between effectors of different modalities (i.e., vocal responses and manual responses) may affect dual-task performance (Bratzke et al., 2008). The occurrence of such cross-modal motor interference may have prevented reliable learning effects with manual motor execution processes in the current dual-task trials.

At this point, it is worth mentioning a potential asymmetry in the applied transfer logic that might affect our conclusions. According to this logic, the observation of performance impairments after changing some aspects of the tasks suggests that something had been learned during practice, and that this has contributed to the observed practice-related speed-up of processing time. However, the opposite conclusion—that is, that no learning has occurred if one does not find a performance change after the transfer changes—seems not to be unequivocal. Theoretically, a result pattern of equal performance before and after transfer might merely show that whatever was learned could be generalized to the new context. For example, the perceptual stage of the visual task might have been shortened, and a change in stimulus from circles to triangles might have had no effect on performance because the perceptual learning was about discerning relative locations, and was not about form. In other words, the routines of shortened form (i.e., circle) processing could be generalized to new forms (i.e., triangles).

In theory, such kind-of-processing generalization could also be proposed for the case of verbal and manual motor processes. However, we assume that the assumption of generalization could not be applied as a sole account to explain any lack of a performance difference after we had changed some processing component in the present transfer sessions. For example, for the specific case of the motor routines, it is not reasonable to assume a generalizable, higher-level routine that could merge specific verbal motor programs or the specific muscles of the motor effectors of different hands. Exemplary evidence inconsistent with the assumption of higher-level routines has come from a study on tapping practice, which showed no perfect transfer to tapping performance with the middle finger of an unpracticed hand after tapping practice with the middle finger of the other hand (Koeneke, Battista, Jancke, & Peters, 2009). Likewise, it is rather implausible to assume higher-level processing routines that could merge many specific forms of perceptual information. For example, in the specific case of the stimulus information presented during practice and stimulus transfer, it is not reasonable to assume higher-level processing routines that would relate to both the specific "circle" and "triangle" information (Exp. 2) or to the specific sine-wave and square-wave tone information (Exp. 1). The findings of perceptual-learning studies are consistent with this assumption: For example, learning to detect tilted lines after visual pop-out practice is specific within basic dimensions such as orientation, size, and position of the practiced visual target, and it does not transfer to contexts with substantial changes relative to the training context (Ahissar & Hochstein, 1997). To explain these findings, it thus requires the assumption of routines focused on specific characteristics; such "specific" routines were tested when we transferred from circles to triangles or from sine- to square-wave tones, and vice versa. Taken together, a careful analysis of the processes and conditions involved allowed us to specify whether the lack of a performance difference was due to an absence of practice effects or to the acquisition of generalized processing routines.

Future research may investigate this issue of higher-level processing routines with manipulations of stimulus and/or motor information that was more or less task-relevant (e.g., in the present visual task: location vs. form manipulation). The generalizability of the present findings could also be tested in single and dual tasks with different characteristics (e.g., varying task intervals in dual tasks) and different component tasks.

Implication for dual-task practice models

Testing stage shortening in the dual-task context of Schumacher et al. (2001) was essential, because this situation generated evidence for the elimination of dual-task costs with practice. On the basis of this evidence, the authors could draw strong conclusions about the processing architecture of a practiced dual task in favor of the strategic engagement of limited-capacity processes in parallel under conditions of extensive practice and the specific combination of the present auditory and visual task. Such processing is realized in the framework of EPIC—an "executive process interactive control" model (Meyer & Kieras, 1997). This model assumes the use of declarative knowledge about the stimulus–response mapping rules (i.e., verbal descriptions of the task requirements) at the beginning of practice and a conversion of that knowledge into procedural knowledge (i.e., into the form of condition–action production rules) after practice with the corresponding mapping conditions (Meyer & Kieras, 1997; Schumacher et al., 2001). When the conversion of the knowledge is completed, the response-selection processes in the two tasks may be executed simultaneously, allowing dual-task costs to be eliminated. The present findings indicate that such a knowledge conversion in the EPIC framework may be characterized by shortening of the response-selection stage. Potentially, EPIC may also explain the observed larger effect of changing central-stage information in a dual task as compared with a single task (i.e., the central-stage manipulation's effect on dual-task costs): Due to the introduction of an unpracticed set of stimulus–response mappings, participants may, in theory, strategically adapt another type of processing scheduling during learning. For example, former parallel scheduling of the response-selection processes might change to more sequential processing. Although nothing in the literature provides reliable evidence for such a strategy change after learning, this assumption shows that a flexible model like EPIC has the power to explain the observed changes in dual-task performance after changes in response selection.

According to the second type of model, the practice-related reduction of dual-task costs is primarily explained by assuming a decrease of the time needed for capacity-limited response-selection processing (Anderson, Taatgen, & Byrne, 2005; Ruthruff et al., 2003; Schubert, 2008). In essence, these models assume that capacity limitations at response-selection stages are structural, unavoidable, and remain existent over practice. One prominent representative of this type of model is the latent bottleneck model. The present findings provide evidence for one key assumption of the latent bottleneck model: namely, the assumption of central-stage shortening (e.g., Ruthruff et al., 2001). A critical finding of the present study, which also needs to be discussed in the context of the latent bottleneck model, is the observation of larger dual-task than single-task RT increases after manipulating the response-selection stages. In particular, these larger RT increases may indicate that the response-selection manipulation during transfer has not only changed the processes within the component tasks but also increases the difficulty of the task coordination processes occurring between these tasks in dual-task trials (Bherer et al., 2005). A number of studies has provided reliable evidence for the existence of such task coordination processes and that these processes are prolonged when new stimulus–response information has to be processed in a transfer session after practice (Liepelt et al., 2011; Strobach, Frensch, Soutschek, & Schubert, 2012).

A further important finding is that, after eight sessions of practice, RT differences between dual-task and single-task trials were greatly reduced, but residual dual-task costs remained. This finding of residual dual-task costs suggests that a complete reduction of these costs is not easily achieved as a result of dual-task practice (Schumacher et al., 2001), which is in line with a range of previous findings (Tombu & Jolicœur, 2004). The residual dual-task costs in the present study might be due to the use of separate deadlines for the dual-task and single-task conditions, which were taken as the basis of the monetary payoff matrix. This procedure might maintain strong motivation for both single-task trials and dual-task trials until the end of practice (Tombu & Jolicœur, 2004). In contrast, Schumacher et al. (2001) exclusively used the performance deadline of single-task trials presented during mixed blocks to award monetary payoffs in both single- and dual-task trials during practice (see also Hazeltine et al., 2002). To reach this deadline, participants in the Schumacher context might have mobilized their effort more in dual-task than in single-task trials. As a result, one should find a greater reduction of RTs in the dual task than in the single task during practice. This difference in deadline procedures between the studies might explain the finding of nonsignificant dual-task costs in Schumacher et al.'s study, in contrast to the small residual dual-task costs that we found at the end of practice in the present study.

Conclusion

To summarize, we found that a practice-related speed-up of central processes contributes to the shortening of the overall task-processing time in both component tasks of a dual task, and to the practice-related reduction of dual-task costs. Additionally, we gained evidence for a speed-up of the processes involved in the initial perception of auditory stimuli. While these findings specify previous findings (e.g., Ruthruff et al., 2001; Sangals et al., 2007) suggesting shortening of premotor processing time in the component tasks, practice did not lead to measurable changes in the execution of simple motor responses in the dual-task context of the present study.

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