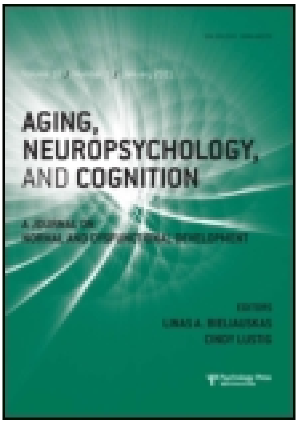

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ABSTRACT

Impaired dual-task performance in younger and older adults can be improved with practice. Optimal conditions even allow for a (near) elimination of this impairment in younger adults. However, practice effects under these conditions in older adults are unknown. Further, it is open, how changed task scheduling and/ or the acquisition of task coordination skills affect the temporal overlap of two tasks in different age groups; this overlap indicate the involvement of these practice-related mechanisms to compensate for impaired dual-task performance. In a dual-task situation of Schumacher et al. (2001, *Psychological Science, 12*, 230) including optimal conditions for dual-task performance, both younger and older adults were able to achieve an improvement in dual-task performance with 8 practice sessions to the same degree. The temporal task overlap changed similarly in both age groups during these sessions demonstrating a similar degree of the involvement of compensation mechanisms in younger and older adults. At the end of practice, however, we showed that older adults do not achieve the same optimized dual-task performance level of younger adults.

Keywords: Cognitive aging; Dual-task performance; Dual-task interference; Practice; Compensation mechanisms.

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Age-related differences in dual-task performance have been demonstrated in numerous dual-task paradigms. In these paradigms, older adults commonly show greater interference in dual-task than in single-task situations with tasks presented in isolation when compared to younger adults (e.g., Allen, Smith, Vires-Collins, & Sperry, 1998; Glass et al., 2000; Hartley, 2001; Hartley & Little, 1999; Hein & Schubert, 2004; McDowd & Shaw, 2000; Verhaeghen, 2011; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). However, irrespective of this difference, a number of studies provided evidence that younger as well as older adults benefit from practice. That is, both age groups are able to optimize dual-task performance and show often reduced dual-task interference after practice (e.g., Allen, Ruthruff, Elicker, & Lien, 2009; Baron & Matilla, 1989; Bherer et al., 2006, 2008; Hartley, Maquestiaux, & Silverman Butts, 2011; Maquestiaux, Hartley, & Bertsch, 2004; Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Maquestiaux, Laguë-Beauvais, Ruthruff, Hartley, & Bherer, 2010); this type of practice-related optimization across different age groups was found for a number of cognitive functions (for a review see Hertzog, Kramer, Wilson, & Lindenberger, 2009).

However, some dual-task practice studies with younger adults have provided evidence for an extremely optimized dual-task performance (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001). These studies demonstrated minimized (and in some cases even eliminated) dual-task interference at the end of practice. While such findings illustrate a promisingly large range of practice-related cognitive plasticity in younger adults, there is, however, no study comparing optimized dual-task performance after practice in younger adults with this performance after practice in older adults (Allen et al., 2009). Such investigation of dual-task practice effects would be interesting for aging research as it may provide more conclusive evidence about cognitive plasticity and its range in older adults (Bherer et al., 2006). In particular, the limits of optimization in dual-task performance in older adults should demonstrate the maximum cognitive performance potential or 'latent' reserve capacity of older adults in a more appropriate way than investigating the cognitive abilities of older people without extensive practice would. Lindenberger and coworkers (Lindenberger & Baltes, 1995; Lindenberger, Kliegl, & Baltes, 1992) have argued that this approach can lead to an identification of true age-related cognitive decline, rather than overestimate age-related differences due to non-optimized testing conditions, assuming that age-related differences in reserve capacity are more accurately assessed near the limits of performance.

Considering the optimization of dual-task performance, several studies have aimed to understand the specific practice-related mechanisms to compensate for dual-task interference (Damos & Wickens, 1980; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Kramer, Larish, & Strayer, 1995; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Ruthruff, Van Selst, Johnston, & Remington, 2006). However, little is known about the character of these compensation mechanisms. In the present investigation of optimal dual-task performance, we follow the assumption that in both younger and older adults these mechanisms can be understood by investigating the temporal relation between the processing streams of two simultaneous tasks. In particular, we assume that an increased amount of temporal overlap of the processing streams of the two component tasks in a dual-task situation results from successful practice-related compensation for dual-task interference and should parallel the practice-related reduction of dual-task interference in both age groups (e.g., Allen et al., 2009; Glass et al., 2000; Meyer & Kieras, 1997a, 1997b).

Meyer and Kieras (1999) listed five prerequisites that allow for the largest possible optimization of dual-task performance: "(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" (p. 54).

Previous attempts to compare practice-related improvements in older and younger adults' dual-task processing have provided impressive findings concerning cognitive plasticity in old age; however, unfortunately, they have not yet considered all of the conditions mentioned earlier and consequently their findings may not be fully conclusive about the possible range of practice-related changes in older adults' dual-task performance. Maquestiaux et al. (2010), for instance, applied a dual-task practice situation that emphasizes response speed for and extensive practice of only one component task (i.e., Condition 1, 3, and 5 of Meyer & Kieras, 1999, are not implemented). In a different line of research, Bherer et al. (2005, 2006) did not include all conditions when applying similar perceptual and motor processors on the component tasks (i.e., Condition 4 not implemented). Thus, the critical questions therefore are: where would be the limit of the practice-related optimization of dual-task performance in older and younger adults? What is the amount of temporal overlap of processing streams on two component tasks in situations with such optimized dual-task performance in the different age groups?

Dual-task Practice Effects Under Optimal Conditions

In research with younger adults, Schumacher et al. (2001) introduced a dual-task situation that considers the requirements for optimal dual-task performance as proposed by Meyer and Kieras (1999; see also Hazeltine et al., 2002; Strobach, Frensch, & Schubert, 2008; Strobach, Liepelt, Schubert, & Kiesel, 2011; Tombu & Jolicoeur, 2004). The authors asked participants to perform a paradigm that consisted of tasks with different perception and motor components: a visual-manual (i.e., the visual task) and an auditory-vocal choice RT task (i.e., the auditory task). The practice procedure requires practicing three different trial types: participants performed only one of the two tasks in single-task blocks (single-task trials); in mixed blocks, participants either responded to only one task (i.e., mixed single-task trials); or actually executed two motor responses to simultaneously presented stimuli in two different tasks (dual-task trials with stimulus onset asynchrony, SOA, of 0 ms). Participants were instructed to respond as fast and as accurately as possible with equal priority and with no pre-specified serial order to both stimuli in these trials. They received adaptive and continuous on-screen feedback as well as performance-based monetary bonuses for optimized RT and error performance; these procedures are consistent with the principles Schmidt and Bjork (1992) expressed for efficient training effects.

The difference in performance between the dual-task and mixed single-task trials provides a measure of the processing necessary to perceive multiple stimuli and coordinate the execution of two responses, which we call *dual-task costs*. After extensive practice, these costs were statistically eliminated with similar RTs in dual-task and both single-task situations (Hazeltine et al., 2002; Schumacher et al., 2001) or were extremely reduced (Liepelt, Strobach, Frensch, & Schubert, 2011; Strobach et al., 2008; Tombu & Jolicoeur, 2004). These findings demonstrate that in dual-task situations, implementing optimal conditions for dual-task performance in the sense of Meyer and Kieras (1999), younger adults show no or extremely reduced costs at the end of practice. The aim of the present study is to test the dual-task performance level of older adults compared to younger adults after 8 practice sessions in Schumacher et al.'s (2001) dual-task situation. This is because this situation obeys all conditions for optimal dual-task performance (Meyer & Kieras, 1999) and enables the investigation of limits in dual-task performance improvements particularly in older adults (Lindenberger & Baltes, 1995; Lindenberger et al., 1992).

Practice-related Mechanisms to Compensate Dual-task Interference

Several studies have aimed to understand the specific practice-related mechanisms to compensate for dual-task interference in younger and older adults (e.g., Kahneman, 1973; Meyer & Kieras, 1997a) as well as to compensate for stronger interference in older compared to younger adults (Li, Lindenberger, Freund, & Baltes, 2001). These mechanisms may modulate the temporal relation and overlapping of processing streams of two tasks (Glass et al., 2000; Meyer & Kieras, 1997a, 1997b, 1999) by setting lockout points and unlocking events within a second task (i.e., the slower component task) and a first task (i.e., the faster component task), respectively. Lockout points in a second task indicate the point in the processing course of this task where processing is temporally stopped, ensuring that the response for a first task can be made before the response in the second task. In contrast, unlocking events in the first task signifies that the processing of this task is sufficiently complete to resume processing of the second task. In particular, an early lockout point (e.g., before response selection) and/or a late unlocking event (e.g., after response selection) are essential to compensate dual-task interference during practice. From a different perspective, compensation mechanisms may be related to the acquisition of improved task coordination skills (e.g., Bherer et al., 2005; Hirst et al., 1980; Kramer et al., 1995; Liepelt et al., 2011; Strobach, Frensch, Soutschek, & Schubert, 2011). These skills are associated with the control of simultaneous task processing streams, e.g., switching between processes of the different component tasks (see more details about task coordination skills later in the Discussion). Moreover, practice-related shortening of processing stages within the component tasks (Ruthruff, Johnston, & Van Selst, 2001; Ruthruff et al., 2003, 2006; Schubert, 1999, 2008) and their processing stages (Pashler & Baylis, 1991) are associated with the reduction of dual-task interference.

We apply distribution analyses of inter-response intervals (IRIs) between simultaneous task responses to analyze the degree of temporal overlap between the two tasks in a dual-task situation. The IRI distribution analyses were conducted in different training sessions for both older and younger adults. We reasoned that if IRIs are large then the amount of temporal overlap between both tasks is smaller, as compared to a situation in which IRIs are small. Consequently, if IRIs are similarly reduced across both aging groups across practice sessions, then this would be consistent with a similarly increasing amount of temporal overlap between component tasks. At the same time, this similar amount of temporal overlap would reflect a similar direction in older and younger participants' efforts to compensate for dual-task interference although the particular kind of compensation mechanism would remain to be specified. In contrast, if the IRIs change differently across practice sessions, then this would point to a different amount of temporal overlap and, consequently, different degrees of the involvement of compensation mechanisms in younger and older adults during practice.

METHOD

Participants

Ten older adults (mean age = 63.3 years, *SD* = 3.4, range 57–68, 5 females) were recruited from a university course for senior adults at Ludwig-Maximilans-University, Munich, Germany. Alternatively, the

TABLE 1. Age, formal education, general health status, attention performance, non-verbal intelligence, and vocabulary knowledge for older and younger adults; MMSE (Mini-Mental State Examination) scores for older adults only; CFT 20-R: Cultural Fair Intelligence Test, WST: Wortschatztest (Vocabulary Test)

	Older adults ($N = 10$)			Younger adults ($N = 10$)		
	M	*SD*	Range	*M*	*SD*	Range
Age (years)	63.6	3.4	57–68	22.7	3.3	19–29
Education (years)	18.0	3.9	13–24	14.2**	1.4	13–16.5
Health status (1–5)	4.4	0.7	3–5	3.7*ns*	1.3	1–5
Attention performance (d2 Test)						
Overall performance	410.9	90.6	284–559	532.9**	80.0	410–632
Concentration performance	144.5	46.3	62–212	204.1**	66.1	94–279
Intelligence test (CFT 20-R) IQ	96.4	18.0	76–134	114.2*	15.4	80–142
Vocabulary test (WST) IQ	114.2	8.6	97–125	107.3*ns*	8.0	92–118
MMSE (maximum score = 30)	29.8	0.4	29–30			

**$p < .01$, *$p < .05$, *ns,* non-significant.

10 younger adults (mean age = 22.7 years, $SD = 3.3$, range 19–29, 5 females) were recruited from the university's bachelor and diploma courses. Both the older and younger adults were paid eight Euros per session plus performance-based monetary bonuses for their participation (for bonus details see later in the Procedure and design section). As shown in Table 1, all participants were generally well-educated, with older adults reporting more years of education ($M = 18.0$ years, $SD = 3.9$ years) than younger adults ($M = 14.2$ years, $SD = 1.4$ years), $t(18) = 2.962$, $p < .01$. On a 5-point health rating scale (1 = *poor health*; 5 = *excellent health*), older and younger adults gave similar mean self-ratings of 4.4 ($SD = 0.7$) and 3.7 ($SD = 1.3$), respectively, $t(18) = 1.544$, $p = .14$. Participants were screened for normal or corrected-to-normal vision and hearing via self-report; we included no participants with hearing aids or eye surgery. Older adults also had no history of neurological diseases, diabetes, or coronary diseases and did not take any medication that might have affected cognition. The Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) indicated no impaired cognitive abilities among the older participants ($M = 29.8$, $SD = 0.4$, range = 29–30). A handedness test (Oldfield, 1971) indicated that participants in both groups were right-handed.

In order to further characterize the participants, we conducted paper-and-pencil tests on attention performance (d2 Test; Brickenkamp & Zillmer, 1998), a non-verbal intelligence test (Culture Fair Intelligence Test, CFT 20-R; Weiss, 2006), and a vocabulary test (Wortschatztest, WST; Anger et al., 1968). As illustrated in Table 1, performance in the d2 Test of overall and concentration scores was higher in younger adults compared with older adults, $t(18) = 3.192$, $p < .01$ and $t(18) = 2.335$, $p < .05$, respectively. Similarly, non-verbal intelligence was optimized in younger adults in contrast with older adults, $t(18) = 2.373$, $p < .05$. The vocabulary test indicated similar vocabulary knowledge in both groups of participants, $t(18) = 1.864$, $p > .08$; such findings demonstrate the typical finding of impaired fluid processing functions but robust crystallized knowledge across aging (e.g., Cavanaugh & Blanchard-Fields, 2006).

Apparatus and Stimuli

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

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

On the auditory task, participants verbally responded to one of three possible sine-wave tones played on headphones with a sound level of 75 dB. They responded by saying 'ONE' to the low frequency tone (350 Hz), 'TWO' to the middle frequency tone (900 Hz), or 'THREE' to the high frequency tone (1650 Hz; German: 'EINS', 'ZWEI', and 'DREI'). Verbal reactions were recorded with a Sony microphone connected to a voice key.

Procedure and Design

A single-task trial started with three white lines serving as placeholders signaling the beginning of a trial for 500 ms. After this period had elapsed, an additional circle appeared in the visual task and remained visible until the participant responded or until a maximum of 2000 ms had elapsed. A tone lasting for 40 ms was played in the auditory task. In dual-task trials, a circle and a tone were presented simultaneously. RTs were given as feedback after each trial for 1500 ms followed by a blank screen for 700 ms. In dual-task trials, only the faster of the two RTs was given as feedback at the end of the trial to minimize the load. When participants committed an error or 2000 ms had elapsed, the RT feedback was replaced by the German word for error ('Fehler') for the same amount of time.

There were two types of blocks: single-task blocks and mixed blocks. In the single-task blocks, participants performed either 45 single-task trials of the visual task or of the auditory task. During mixed blocks, participants performed a mixture of 30 single-task trials (mixed single-task trials), 15 of the visual task and 15 of the auditory task, and 18 dual-task trials. All trials were randomly intermixed, requiring participants to switch between processing different single- and dual-task trials. Participants were instructed to respond to both stimuli as quickly and accurately as possible during all blocks, to give these their full concentration and to give both tasks equal priority.

In Session 1, participants performed six visual and six auditory single-task blocks that were presented in an alternating order. Half of the participants started with a visual and the other half with an auditory single-task block. Session 2 included six single-task blocks (3 visual and 3 auditory single-task blocks) and eight mixed blocks. After two initial single-task blocks (1 visual and 1 auditory single-task block), sequences of two mixed blocks and one single-task block followed. The order of single-task blocks (first visual or auditory) was counterbalanced across participants. The design in Sessions 3 to 8 was identical to that in Session 2 but these sessions included two additional mixed blocks at the end. While Session 1 lasted around 45 minutes the following sessions took about 60 minutes. Sessions were conducted on successive days (excluding weekends).

To maximize participants' motivation for achieving fast performance, reward was given in the form of a monetary performance-based payoff in the hybrid and single-task practice groups (see also Schumacher et al., 2001; Tombu & Jolicoeur, 2004). The payoff matrix was based on an adaptive comparison between participant's RT in a current block and a reference RT; this reference RT represents the individual best mean block RT and is adjusted separately for the visual and the auditory task and for task conditions (single-task trials in single-task blocks vs. dual-task trials). Participants could earn the more money the nearer the current RTs were to the reference RTs or if current block RTs were faster than the reference RTs; in the latter case reference RTs were adjusted to current block RTs. Bonus payments were also made on the basis of accuracy rates: A bonus was given for each correct response while there was a deduction from this bonus for each incorrect response.

RESULTS

Prior to statistical RT analyses, we excluded all trials in which responses were incorrect (6.9 %). The first session was considered as practice and was excluded from further analyses.

Dual-task Practice Data in Older and Younger Adults

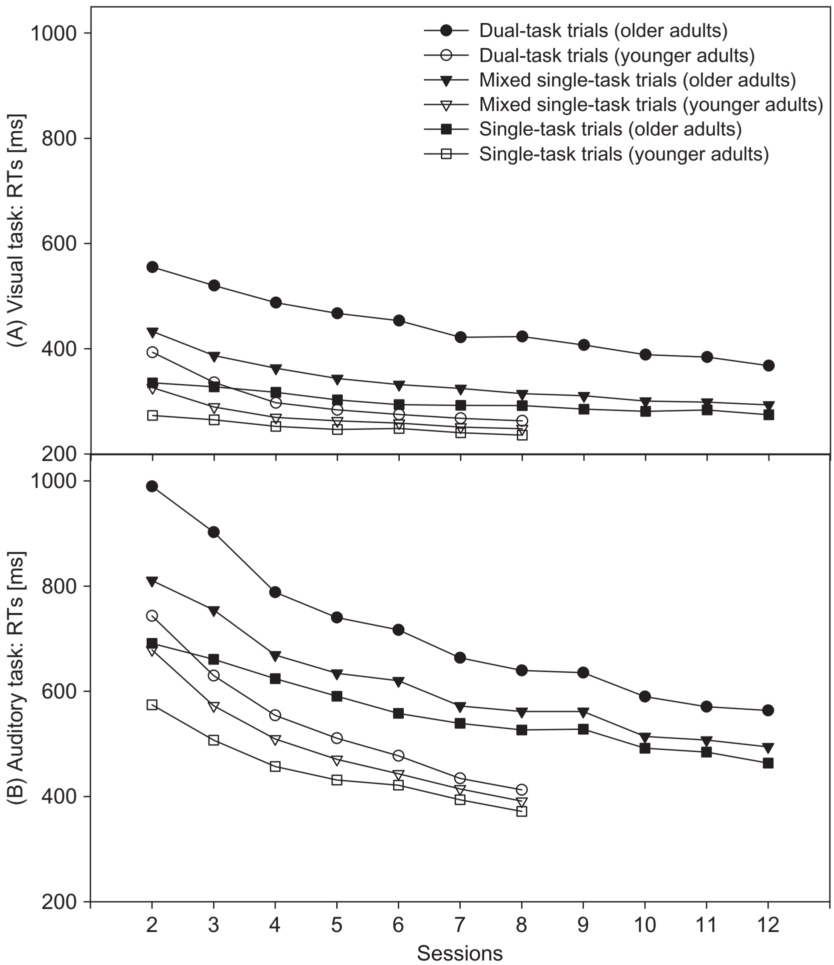
For the analysis of the practice data, we conducted 7 × 3 × 2 mixed measures ANOVAs with the within-subject factors SESSION (Sessions 2 to 8) and TRIALTYPE (single-task trials, mixed single-task trials, and dual-task trials) as well as the between-subject factor AGE GROUP (younger adults vs. older adults) on RTs and error rates separately for each component task. Our primary indicator of dual-task performance was the difference between dual-task trials and mixed single-task trials that reflects dual-task costs. In addition, we report the difference between mixed single-task trials and single-task trials that reflects task-set costs; this measure demonstrates the requirement to prepare for and maintain multiple task sets in mixed single-task conditions as compared with the condition of single-task blocks (Bherer et al., 2005; Rogers & Monsell, 1995).

RT Analyses

As illustrated in Figure 1A, RTs in the *visual task* declined considerably during practice, $F(6, 108) = 51.419$, $p < .001$, partial $\eta_p^2 = .74$. The typical main effect of AGE GROUP was found that younger adults responded faster than older adults, $F(1, 18) = 23.666$, $p < .001$, partial $\eta_p^2 = .57$. RTs also differed between trial types, $F(2, 36) = 40.557$, $p < .001$, partial $\eta_p^2 = .69$, indicating higher RTs in dual-task trials followed by mixed single-task trials, and single-task trials. TRIALTYPE was qualified by an interaction with AGE GROUP, $F(2, 36) = 12.079$, $p < .001$, partial $\eta_p^2 = .40$, and with SESSION, $F(6, 108) = 12.851$, $p < .001$, partial $\eta_p^2 = .41$. Dual-task as well as task-set costs were increased in older compared to younger adults. Both types of costs decreased during practice across both age groups. A lacking interaction of SESSION, TRIALTYPE, and AGE GROUP indicated that the practice-related reduction of dual-task and task-set costs was similar in both groups of participants, $F(12, 216) = 1.170$, $p > .31$, partial $\eta_p^2 = .06$; this similar reduction is clarified by log–log plots in Figure 2. As illustrated in Figure 3, older adults showed larger dual-task costs than younger adults (older adults: 109 ms, $t(9) = 5.652$, $p < .001$; younger adults: 15 ms, $t(9) = 3.815$, $p < .01$; in a between group comparison: $F(1, 18) = 22.716$, $p < .001$, partial $\eta_p^2 = .56$) while task-set costs showed no statistical difference (older adults: 22 ms, $t(9) = 4.675$, $p < .001$; younger adults: 12 ms, $t(9) = 2.955$, $p < .05$; in a between group comparison: $F(1, 18) = 2.772$, $p > .12$, partial $\eta_p^2 = .13$) at the end of practice (i.e., Session 8). Repeated contrasts localized these similar task-set costs between groups exclusively in Session 8, while all previous sessions showed an advantage for younger adults, $F(1, 18) > 4.476$, $p < .05$, partial $\eta_p^2 > .20$.

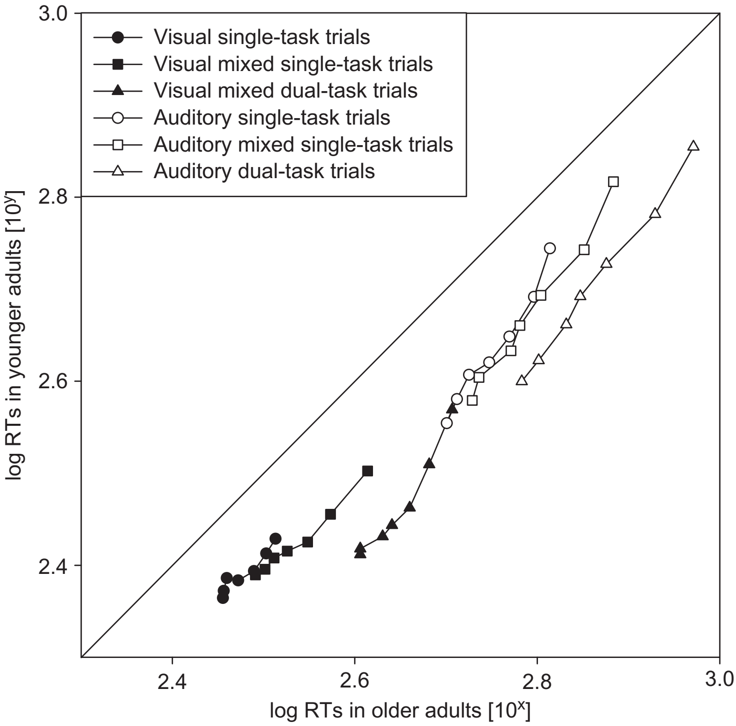
For the *auditory task* (Figure 1B), RT data showed faster responses at the end than at the beginning of practice, $F(6, 108) = 132.860$, $p < .001$, partial

FIGURE 1. Mean reaction times (RTs) in milliseconds (ms) in single-task trials of single-task blocks, single-task trials in mixed blocks (mixed single-task trials), and dual-task trials for (A) the visual task and (B) the auditory task across Sessions 2–12 (older adults) or Sessions 2–8 (younger adults).



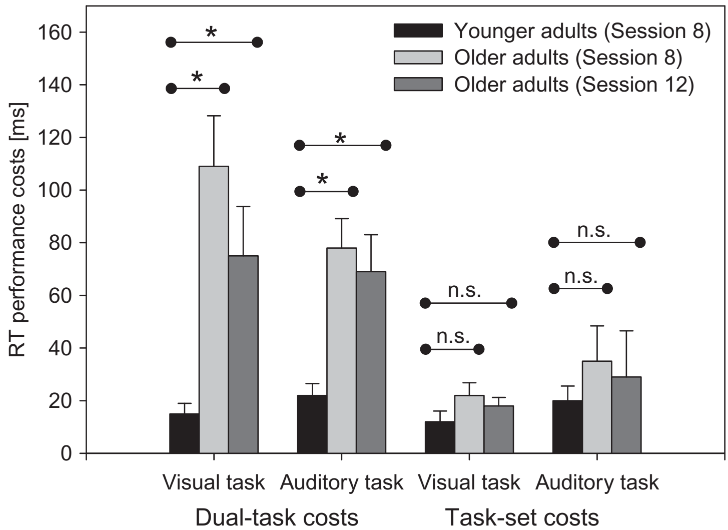
$\eta_p^2 = .88$. RTs were lower in single-task, than in mixed single-task and in dual-task trials, $F(2, 36) = 52.260$, $p < .001$, partial $\eta_p^2 = .74$. The typical main effect of AGE GROUP was found in that younger adults responded faster than older adults, $F(1, 18) = 14.431$, $p < .001$, partial $\eta_p^2 = .45$. The group difference was qualified by an interaction with TRIALTYPE, $F(2, 36) = 7.140$, $p < .01$, partial $\eta_p^2 = .28$. Similar to the visual-task RTs, older adults showed larger dual-task costs as well as larger task-set costs than younger adults across practice. A significant interaction of SESSION

FIGURE 2. Log-log transformed reaction times (RTs) in single-task, mixed single-task, and dual-task trials of visual and auditory tasks in younger and older adults; each data point represents one of the practice sessions 2-8. Distributions located in parallel to the y = x-line reflect similar practice related improvements in younger and older adults. Locations below this line reflect generally slower responses in older adults.



and TRIALTYPE, $F(12, 216) = 22.812$, $p < .001$, partial $\eta_p^2 = .56$, indicated that dual-task and task-set costs decreased during practice across both age groups. A lacking interaction of SESSION, TRIALTYPE, and AGE GROUP indicated that the effect of practice on performance costs was similar in both groups of participants, $F(12, 216) = 1.496$, $p > .13$, partial $\eta_p^2 = .08$; this reduction similarity is clarified by log–log plots in Figure 2. As illustrated in Figure 3, older adults showed larger dual-task costs than younger adults (older adults: 78 ms, $t(9) = 6.990$, $p < .001$; younger adults: 22 ms, $t(9) = 4.787$, $p < .001$; between group comparison: $F(1, 18) = 21.964$, $p < .001$, partial $\eta_p^2 = .55$) while task-set costs showed no statistical difference (older adults: 35 ms, $t(9) = 2.633$, $p < .05$; younger adults: 20 ms, $t(9) = 3.529$, $p < .01$; between group comparison: $F(1, 18) = 1.171$, $p > .29$, partial $\eta_p^2 = .06$) at the end of practice (i.e., Session 8). Repeated contrasts indicated no significant difference between younger and older adults in all

FIGURE 3. Dual-task and task-set costs in younger and older adults at the end of practice (Session 8, respectively, 12) in reaction times (RTs).



sessions except for Session 6, $F(1, 18) = 7.309$, $p < .05$, partial $\eta_p^2 = .29$; in this session, task-set costs were higher in older adults.[1]

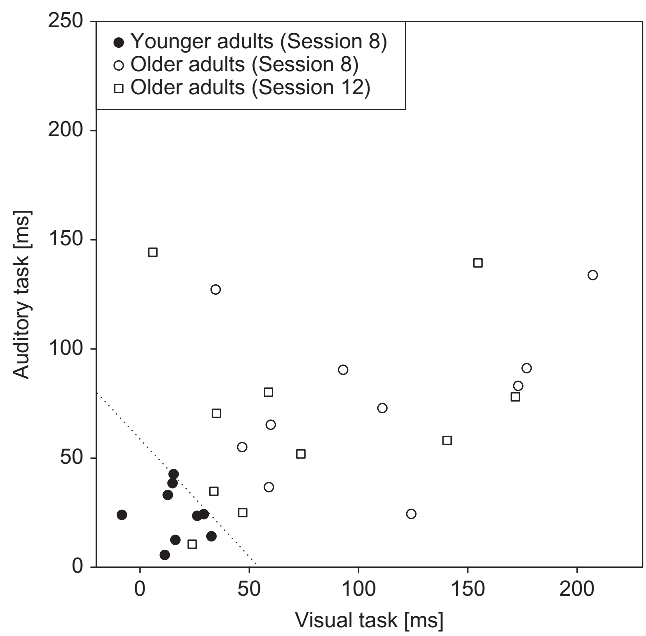
As the given group sizes are relatively small, the lacking difference of dual-task practice benefits in the two groups (observed for both tasks) could be due to a lack of power. Therefore, one could argue that an increase of the group size may have revealed latent differences between the two groups. In order to test this assumption we performed a power analysis that demonstrated that the finding of a comparable amount of the RT performance improvement in both groups was quite robust. Given ά, power, and the effect size of the present experiment, the interaction of SESSION, TRIALTYPE, and AGE GROUP in the visual and auditory tasks would still not reach a significant value if we had included more than 120 participants in both age groups (G*Power: Faul, Erdfelder, Buchner, & Lang, 2009).

In the preceding analyses we used a strong and reliable criterion for measuring dual-task performance, by assessing dual-task costs in the RT comparison of dual-task trials and mixed single-task trials (Bherer et al., 2006; Hazeltine et al., 2002). However, this criterion may lead to

[1] An increased amount of education in older compared with younger adults (see Table 1) had no impact on effects on and interactions with AGE GROUP (i.e., the interaction of AGE GROUP and TRIALTYPE) in RT analyses of the practice data. These effects and interactions remained significant in analyses of the visual and auditory task when *years of education* were introduced as a covariate into the mixed measures ANOVAs including the factors SESSION, AGE GROUP, and TRIALTYPE.

interpretative difficulties if there were baseline differences in performance due to the general slowing of processing in older adults (Guttentag, 1989; Riby, Perfect, & Stollery, 2004; Somberg & Salthouse, 1982); in fact, this might have obscured possible differences in dual-task performance in Session 8 for the visual and auditory RT data. Therefore, we additionally assessed dual-task performance in terms of *proportional dual-task costs* to control for baseline differences between the age groups: (dual-task RTs–mixed single-task RTs)/mixed single-task RTs (Riby et al., 2004). The analyses of proportional dual-task costs corroborated the findings in the analyses of dual-task costs: Older adults showed larger proportional dual-task costs in the visual task, $t(18) = 5.119$, $p < .001$, and the auditory task, $t(18) = 4.387$, $p < .001$, than younger adults at the end of practice. Thus, the appearance of dual-task cost differences between both age groups is not confounded by possible differences in single-task performance between groups; therefore a general slowing in older adults cannot completely explain the observed differences in dual-task costs at the end of practice.

FIGURE 4. Individual dual-task reaction time (RT) costs in the younger and older adults at the end of practice (i.e., younger adults: Session 8, older adults: Sessions 8 and 12). The *x*-axis represents the costs in the visual task while the *y*-axis represents the costs in the auditory task. The dotted line with a slope of −1 defines the area of optimized dual-task performance in younger adults.



In addition, we analyzed whether the mean dual-task advantage in younger adults compared with older adults also holds at an individual level of data analysis (Hartley et al., 2011; Schumacher et al., 2001). For that purpose, we plotted the dual-task costs in Session 8 of the visual and the auditory task for each individual older and younger adult in Figure 4. In this Brinley plot, data points for individual participants with lower costs in both tasks are located in the lower left corner while participants with larger costs are located in the upper right corner. Data points for younger adults are mostly in the lower left corner that represents relatively low dual-task costs of both tasks in Session 8. Alternatively, data points of all individual older adults are at positions that represent larger costs and impaired dual-task performance relative to younger adults. The observed difference in mean dual-task costs between the age groups at the end of practice, therefore also holds at an individual level.

Summarizing the RT data, older adults showed a similar practice benefit in dual-task and task-set costs than younger adults. Analyses at the end of practice revealed that at least task-set costs were similar in both groups. However, dual-task costs were still larger in older than in younger adults.[2]

Error Analyses

In the *visual task* (Table 2), there were lower error rates for mixed single-task trials than in single-task and dual-task trials, $F(2, 36) = 14.436$, $p < .001$, partial $\eta_p^2 = .45$. The interaction of SESSION and TRIALTYPE, $F(12, 216) = 3.279$, $p < .001$, partial $\eta_p^2 = .15$, demonstrated that particularly dual-task costs were reduced during practice while task-set costs remained constant across both groups. The interaction of TRIALTYPE and AGE GROUP, $F(2, 36) = 5.013$, $p < .05$, partial $\eta_p^2 = .22$, indicated that younger adults particularly showed decreased task-set costs. However, this decrease

[2] For younger adults, there was an extreme reduction of dual-task costs but no complete statistical elimination of these costs in the Schumacher et al. (2001) paradigm. This is not consistent with previous studies that applied this paradigm and showed statistical evidence for eliminated dual-task costs at the end of practice (Hazeltine et al., 2002; Schumacher et al., 2001). However, the finding of residual costs is similar to other studies that applied this paradigm (Liepelt, Strobach et al., 2011; Strobach et al., 2008; Tombu & Jolicoeur, 2004). These findings show possible boundary conditions to obtain perfect dual-task performance in this paradigm. The finding of residual dual-task costs in the present study might be due to the use of separate deadlines for dual- and single-task conditions taken as the basis of the financial payoff matrix. This procedure might maintain strong motivation for both single- and dual-task trials until the end of practice (Tombu & Jolicoeur, 2004). In contrast, Schumacher et al. (2001) exclusively used the performance deadline of mixed single-task trials presented during the mixed blocks to award financial payoff in both single- and dual-task trials during practice. The Schumacher et al. procedure may increase effects of mobilized effort in dual-task trials as compared to single-task trials. As a result of this, one should find a greater reduction of RTs in dual tasks than in single tasks during practice. This difference in deadline procedures between studies might explain the finding of non-significant dual-task costs in the study of Schumacher et al. in contrast to the small residual dual-task costs we found at the end of practice.

TABLE 2. Error rates in percent in single-task trials of single-task blocks, single-task trials in mixed blocks (mixed single-task trials), and dual-task trials for the visual task and auditory task in older and younger adults across Sessions 2–12 (older adults) or Sessions 2–8 (younger adults)

		Older adults			Younger adults		
Task	Session	Single-task trials	Mixed single-task trials	Dual-task trials	Single-task trials	Mixed single-task trials	Dual-task trials
Visual task	**2**	1.8	0.4	2.3	2.3	0.4	3.9
	3	1.4	1.0	3.1	3.0	1.0	2.2
	4	1.6	0.7	2.7	3.9	1.5	2.1
	5	1.8	0.5	2.2	4.0	1.3	1.9
	6	2.0	1.5	2.6	4.7	1.3	1.8
	7	2.0	1.0	1.5	5.7	2.3	2.5
	8	2.4	0.8	1.3	4.9	1.9	2.6
	9	2.1	1.3	1.4			
	10	3.1	1.2	0.8			
	11	3.2	1.3	0.8			
	12	3.3	1.5	0.6			
Auditory task	**2**	10.7	13.5	16.6	4.1	3.7	6.3
	3	11.5	11.4	12.3	3.3	3.4	5.8
	4	8.4	9.0	12.0	1.9	3.0	3.9
	5	6.6	7.6	10.6	3.1	2.4	5.4
	6	9.3	6.9	9.8	6.1	4.5	5.7
	7	6.0	7.9	9.2	5.1	4.5	5.8
	8	7.0	5.8	7.3	3.9	3.5	5.6
	9	6.7	6.7	9.8			
	10	7.8	7.0	10.0			
	11	8.2	6.8	8.7			
	12	8.2	6.8	9.2			

originates from the observation of higher error rates in single-task trials compared to those of older adults. Further, younger adults, when compared with older adults, particularly showed higher error rates at the end of practice (Session 8) while there was no difference at the beginning of practice (i.e., Session 2), $F(6, 108) = 2.416$, $p < .05$, partial $\eta_p^2 = .12$. The observation of increasing error rates with practice found in younger adults is consistent with previous findings (e.g., Hazeltine et al., 2002). However, such an increase is not evident in older adults. It may be explained by a reduced degree of attentiveness in the visual task due to reduced processing demands in younger adults and/ or by cautious visual task performance in older adults by avoiding erroneous responses in single-task trials and at the end of practice.

As illustrated in Table 2, error rates in the *auditory task* were higher in dual-task trials than in mixed single-task and single-task trials, $F(1, 18) = 19.400$, $p < .001$, partial $\eta_p^2 = .52$, and in Session 2 than in

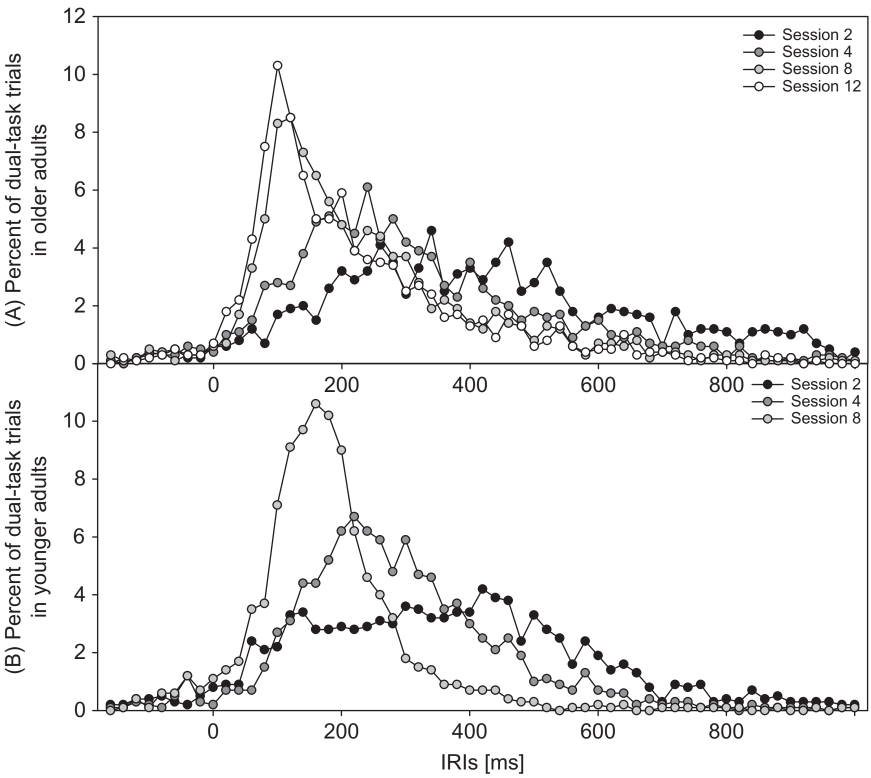
Session 8, $F(6, 108) = 5.895$, $p < .001$, partial $\eta_p^2 = .25$. SESSION was further moderated by an interaction with AGE GROUP, $F(6, 108) = 6.381$, $p < .001$, partial $\eta_p^2 = .26$. While older adults showed larger error rates than younger adults in Session 2; this difference was eliminated in Session 8. The significant interaction of SESSION and TRIALTYPE, $F(12, 216) = 2.094$, $p < .05$, partial $\eta_p^2 = .10$, reflects a practice-related reduction of dual-task costs as well as task-set costs across both groups of participants. In sum, the error data of the visual and the auditory task provide no support for the finding of similar practice benefit on dual-task and task-set costs in older and younger adults across practice sessions.

The error rate analysis in the auditory task allowed us to screen older participants for their hearing ability. This is particularly important because older adults may use high level cognitive processes to compensate for sensory loss, which create added sensory processing costs on top of the dual-task condition (Schneider & Pichola-Fuller, 2000). This sensory loss should be most pronounced at the high frequency range, i.e., for the high tone of 1650 Hz in the auditory task. However, the error rate analysis for Session 1 showed no such deficit in older adults for high compared to the low and the middle tones, $F(2, 18) < 1$; similar RT analysis supported these findings, $F(2, 18) = 2.678$, $p > .10$, partial $\eta_p^2 = .23$. These findings provide no evidence for the assumption of added sensory processing costs on top of dual-task processing.

Distribution of IRIs Across Practice

Next, we analyzed the IRI distributions for older and younger adults in dual-task situations. For this purpose, we calculated the IRIs from the difference of auditory dual-task RTs minus visual dual-task RTs for each dual-task trial in Sessions 2, 4, and 8 in younger and older adults; positive IRIs reflects larger auditory than visual-task RTs while negative IRIs indicate larger visual than auditory-task RTs. For calculating the IRI distributions we subdivided the resulting IRIs in bins of 20 ms; we then calculated the frequency of trials for each IRI bin and plotted the corresponding IRI distributions separately for each session and for each individual age group in Figure 5. Consistent with our assumptions, we observed that the distributions shift from (positively) increased IRIs to decreased IRIs across sessions; this is reflected by a shift in the peaks of IRI distributions from right to left along the *x*-axis. The results of a mixed measures ANOVA on the medians of the individual IRI distributions in these SESSIONs (i.e., Session 2, 4, and 8) and both AGE GROUPs (older adults vs. younger adults) support the impression of a left-shift of IRI distributions towards smaller IRIs; this analysis revealed an effect of SESSION, $F(2, 36) = 48.262$, $p < .001$, partial $\eta_p^2 = .73$. Planned *post-hoc* analyses demonstrated significant median shifts

FIGURE 5. Frequency distribution (in percent) of inter-response intervals (IRIs) in dual-task trials of 20-ms bins. Panel (A) Session 2, Session 4, Session 8, and Session 12 in older adults. Panel (B) Session 2, Session 4, and Session 8 in younger adults.



from Sessions 2 to 4, $F(1, 18) = 17.000$, $p < .001$, partial $\eta_p^2 = .49$, and from Session 4 to 8, $F(1, 18) = 46.756$, $p < .001$, partial $\eta_p^2 = .72$, across both age groups. Importantly, a lacking effect of and a lacking interaction with AGE GROUP, $F(1, 18) < 1$ and $F(2, 36) < 1$, respectively, indicated that the amount of the practice-related IRI change and the change in the temporal relations in processing simultaneous tasks were not different across the two age groups. Thus, these findings demonstrate that both older and younger adults perform two tasks with similar temporal overlap during the course of practice. Together with the observation of a lacking influence of practice on the amount of age-related differences in dual-task costs, this finding points to a similar efficiency of compensation mechanisms to change dual-task performance in older and younger adults.

Figure 5 also shows broad IRI distributions at the beginning of practice while these distributions are relatively sharp at the end of practice. This sharpening may demonstrate that the variability of task overlap is increased at the beginning of practice but this variability decreases from Sessions 2 to 4 and 8. Such decreased variability is an indicator for an increased consistency of temporal task overlap with practice (Logan, 1988; Rickard, 1997). A mixed measures ANOVA on the standard deviations of individual IRI distributions in these SESSIONs (Sessions 2, 4, and 8) and both AGE GROUPs (older adults vs. younger adults) provided statistical evidence for this observation: There was an exclusive effect of SESSION, $F(2, 36) = 33.011$, $p < .001$, partial $\eta_p^2 = .65$, with reduced standard deviations from Sessions 2 to 4, $F(1, 18) = 16.596$, $p < .001$, partial $\eta_p^2 = .48$, and from Sessions 4 to 8, $F(1, 18) = 41.502$, $p < .001$, partial $\eta_p^2 = .70$, in planned *post-hoc* comparisons. This reduction reflects the fact that the variability in overlapping task processing reduces with an increasing amount of practice and this reduction is similar in both groups.

Effects of an Enlarged Amount of Practice on Older Adults' Performance

Next, we tested whether an additional amount of practice in older adults may lead to further improvement in their dual-task performance and consequently, to a performance level of this group approaching that of the younger group with less amount of practice. For this purpose, the older adults performed four additional practice sessions with the Schumacher et al. (2001) task situation following the completion of the eight practice sessions. These Sessions 9 to 12 were identical to the previous sessions (i.e., Sessions 3 to 8). Note that the inclusion of four additional practice sessions in older adults elevated their amount of dual-task practice to more than 150% of the amount in younger adults.

The effects of additional practice in older adults (i.e., Session 12), compared with younger adults (i.e., Session 8) on dual-task and task-set costs were analyzed with mixed measures ANOVAs including the within-subject factor TRIALTYPE (single-task trials, mixed single-task trials, and dual-task trials) as well as the between-subject factor AGE GROUP (younger adults vs. older adults). The combination of both factors is most important for investigating performance costs after additional practice in older adults. Visual-task RTs revealed an interaction of TRIALTYPE and AGE GROUP, $F(2, 36) = 9.539$, $p < .001$, partial $\eta_p^2 = .35$. Dual-task and task-set costs amounted to $M = 75$ ms and $M = 18$ ms in older adults, respectively (Figures 1 and 3). Dual-task costs in older adults were still larger than the corresponding costs in younger adults ($M = 15$ ms) of Session 8, $F(1, 18) = 9.586$, $p < .01$, partial $\eta_p^2 = .35$, while task-set costs did not differ between groups (younger adults: 12 ms), $F(1, 18) = 1.691$, $p > .21$, partial $\eta_p^2 = .08$. For the auditory task, we found an interaction of TRIALTYPE and AGE GROUP, $F(2, 36) = 4.913$, $p < .05$, partial $\eta_p^2 = .22$, for the RT data. Here, the dual-task and task-set costs amounted to $M = 69$ ms and

$M = 31$ ms in older adults respectively (Figures 1 and 3) and the dual-task costs in older adults remained inflated compared to those of the younger adults ($M = 22$ ms) in Session 8, $F(1, 18) = 10.444$, $p < .01$, partial $\eta_p^2 = .37$; task-set costs were not significantly different between the two age groups (younger adults: 20 ms), $F(1, 18) < 1$. Thus, four additional practice sessions in older adults do not allow for similar dual-task performance costs when compared with the costs in younger adults in the task situation of Schumacher et al. (2001). The error rates in the visual task were increased in younger compared to older adults, $F(1, 18) = 5.560$, $p < .05$, partial $\eta_p^2 = .24$, while they were similar between groups in the auditory task, $F(1, 18) = 1.669$, $p > .22$, partial $\eta_p^2 = .08$. There was no evidence for different performance costs between groups, Fs(1, 18) < 1 (Figure 5).

Illustrations of individual dual-task costs in the visual and auditory task revealed that after additional four practice sessions, most of the older adults could not reach the dual-task performance level of younger adults in Session 8 (Figure 4). Only one older adult showed data at a performance level approaching that of the younger adults.

We also analyzed the temporal relation in processing the two tasks and its development from Sessions 8 to 12 in the group of older adults: Does this relation continuously change with an increasing amount of practice in older adults? Such a further change might be reflected in an increased amount of task overlap and by reduced variability in such overlap in dual-task trials. The analysis of the medians demonstrated no further practice-related change across the sessions, $t(9) = 1.109$, $p > .30$, while the standard deviation showed a significant reduction, $t(9) = 2.946$, $p < .05$, as illustrated in Figure 5. Thus, an increasing amount of practice leads to a reduced variability in task overlap but not to a further enlargement of the temporal overlap between the two component tasks. Therefore, older adults can only partly use the additional amount of practice to further compensate dual-task interference.

DISCUSSION

In the present study we analyzed dual-task performance in older and younger adults during single- and dual-task practice with the Schumacher et al.'s (2001) paradigm. This paradigm was supposed to obey all conditions for optimal dual-task performance according to Meyer and Kieras (1999) and thus, represents an appropriate tool to analyze the limits of age-related performance improvements. The findings showed: first, comparing the practice benefit on the dual-task costs of the visual and auditory task, this benefit is similar for younger and older adults (e.g., Allen et al., 2009; Baron & Matilla, 1988; Bherer et al., 2006, 2008). Second, we found indicators for a similar impact of mechanisms to compensate for dual-task performance impairment with practice in older and younger adults (Allen et al., 2009; Glass et al., 2000). Third, at the end of practice, dual-task costs were consistently larger in older compared with younger adults, even after the older adults had additional practice.

Practice Effects on Dual-task Performance in Younger and Older Adults

The finding of reduced dual-task costs in the paradigm of Schumacher et al. (2001) in younger and older adults is consistent with former research in this paradigm (e.g., Hazeltine et al. 2002; Strobach et al., 2008; Tombu & Jolicoeur, 2004) and other dual-task paradigms in younger adults (e.g., Ruthruff et al., 2006; Van Selst, Ruthruff, & Johnston, 1999). However, the present findings allow for an extension of the dual-task practice effect in the Schumacher et al.'s (2001) paradigm to the dual-task performance of older adults (see Hartley et al., 2011, for an extension to an unconventional derivate of that paradigm). While previous studies on dual-task practice in older adults could simply show a practice-related improvement of older adults' dual-task performance (e.g., Bherer et al., 2005; Göthe, Oberauer, & Kliegl, 2007; Kramer et al., 1995), the present findings show similar consequences of dual-task practice (i.e., similar reduction of dual-task costs) in younger and in older adults; note that this was possible under the optimal task conditions for dual-task practice (Meyer & Kieras, 1999).

However, despite the observed similar amount in a practice-related improvement of dual-task costs in older and younger adults, we found a generally impaired dual-task performance (i.e., increased dual-task costs) in older compared to younger adults at the end of practice; even four more practice sessions could not lead to a disappearance of this difference. These findings suggest that older adults are impaired in those processes necessary to perceive multiple stimuli and to coordinate the execution of two responses at the end of practice. We assume that the difference in dual-task performance remaining between the age groups at the end of practice is due to an age-related cognitive decline and that there was no overestimation of age-related differences due to non-optimized conditions for testing (e.g., Bherer et al., 2006; Lindenberger et al., 1992). Such a conclusion was not possible in earlier studies, which did not consider or apply all conditions required for optimal dual-task performance as per Meyer and Kieras (1999). One option to explain the age-related difference in dual-task costs at the end of practice may be to consider possible differences in basic cognitive functions as assessed by neuropsychological tests in the present study. In fact, these tests provide evidence for increased performance in fluid aspects of processing (i.e., CFT 20-R) and attention performance (i.e., d2 Test) in younger as compared to older adults, while no difference for crystallized knowledge (i.e., WST) was evident. In particular, the former two aspects may enable improved abilities to process complex task situations including two component tasks and task coordination processes in younger adults at the end of practice. In contrast to such an impact of higher executive functions, age-related differences in basic sensory abilities appeared not to have a decisive impact on the current findings. Thus, the findings of an additional auditory-task analysis in Session 1 provided no evidence that a potential loss of hearing abilities for particular high frequencies may have affected the dual-task performance of older adults.

Similar to the findings on dual-task costs, we found a parallel reduction of task-set costs in older and younger adults across practice. However, unlike dual-task costs, the task-set costs were similar in both groups at the end of practice. This suggests a similar degree of performance in both younger as well as older adult groups in situations requiring the preparation and maintenance of multiple task sets in situations in which one of several task sets have to be processed (Bherer et al., 2005; Kray & Lindenberger, 2000). This observation contradicts the findings of Bherer et al. (2005, 2006) which showed larger task sets cost in older compared to younger adults in similar situations. This discrepancy in findings may result from the combination of two manual tasks in the Bherer et al. studies and the manual–verbal response combination in the present study. The application of manual responses in the Bherer et al. studies in both tasks lead to repetitions of manual finger responses across the two hands within dual-task trials (e.g., responses with the left and right index fingers). Such repetitions lead to impaired task performance and may avoid a reduction of task-set costs in older adults (Kleinsorge, 1999). Such response repetitions were reduced in the present study and this reduction may allow for similarly minimized task-set costs in younger and older adults.

An additional aspect that may have led to the observed discrepancy between the task-set costs in the Bherer et al. (2005, 2006) studies and the present study was that we included performance feedback plus performance-based monetary bonuses, while Bherer and colleagues exclusively included performance feedback. We think however that this difference between the studies has no crucial impact on the task-set costs because the present performance-based monetary bonuses focused on dual-task and single-task trials but not on mixed single-task trials. An improved performance particularly in mixed single-task trials is essential to reduce task-set costs (i.e., the difference between mixed single-task minus single-task trials). Therefore, we assume that the inclusion of monetary bonuses is of marginal importance to the reduction of the particular task-set costs in the current study. However, note that for the particular case of dual-task costs (different to that of task-set costs) Tombu and Jolicoeur (2004) have shown that the manipulation of performance deadlines for bonuses can determine between optimized (i.e., extremely minimized dual-task costs) and non-optimized dual-task performance at the end of practice.

Practice-related Mechanisms to Compensate for Dual-task Impairment in Older and Younger Adults

Based on the finding of reduced dual-task costs with practice we investigated indicators of practice-related mechanisms to compensate for these costs in older and younger adults. In particular, we focused on the temporal relation of the two processing streams of the component tasks in a dual-task situation. Two aspects of the related analysis of the IRI distributions provided evidence for practice-related changes in this temporal relation: the practice-related shifts of the IRI distributions from larger to smaller IRIs and the reduction in the variability of IRIs. Because these changes in IRI distributions were similar in both younger and older adults (see Results section), we assume a similar direction of those compensation mechanisms, which are applied by both aging groups to cope with the dual-task interference. These mechanisms, however, do not enable a complete adjustment of the amount of dual-task impairments in older adults up to the level of younger adults after practice.

The specific characteristics of these mechanisms may range from optimized task coordination skills (e.g., Liepelt et al., 2011; Strobach, Frensch, et al., 2011) to an optimized scheduling of task processes (e.g., Meyer & Kieras, 1997a) and shortenings of these processes (e.g., Ruthruff et al., 2006). In particular, for younger adults, the findings from our lab provided evidence for a practice-related optimization of task coordination skills. Such skills may result in a speeded switch between task processing stages in two tasks. Liepelt et al. (2011) located this switch after the perception and response selection stages in a faster task and before the response selection and motor stages in a slower task. In the present paradigm, such a speeded switch would have mainly affected the auditory task because this task is typically the slower task (so, auditory response selection is located after that stage in the faster visual task and a potential switch between tasks) in the current paradigm. In case of a speeded switch, the response and motor stages of the auditory task would start earlier after the end of the response selection stage in the visual task and this would lead to shorter auditory dual-task RTs and reduced IRIs after practice.

The assumption of a speeded switching operation in older adults contrasts assumptions of Maquestiaux et al. (2004) who assumed that this operation is not affected by practice in this age group. The discrepancy between our assumptions and those of Maquestiaux et al. (2004) could be that the latter study used highly complex tasks (i.e., one 4-choice and one 8-choice task) while we applied two rather simple tasks. The inclusion of relatively simple tasks may have reduced the load on working memory when preparing for dual tasks in the current situation compared to that of Maquestiaux et al. (Hartley & Little, 1999) and this may have enabled a faster switch between the two component tasks in the current compared to that task situation. Mayr (2001) showed that difficulties in the ability to maintain and to separate two different task sets in working memory are an important factor that determines older adults' difficulties when coping with the need to switch between two tasks. The present findings are consistent with the assumption that practice may lead to an improvement of a switching operation under optimal task conditions even in older adults. However, further studies are necessary to prove that assumption in more detail.

CONCLUSION

The present study demonstrated that younger and older adults were able to achieve a similar improvement of dual-task performance over practice. Practice-related mechanisms to compensate for impaired dual-task performance allow for this improvement and for an increased temporal overlap of the two concurrent task streams in these two age groups. However, we showed that on including the present optimal dual-task conditions, older adults do not achieve the same optimized dual-task performance level of younger adults at the end of practice. Older adults could even not compensate for this performance difference with extra practice.

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