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Testing the limits of cognitive plasticity in older adults: Application to attentional control

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Abstract

Laboratory based training studies suggest that older adults can benefit from training in tasks that tap control aspects of attention. This was further explored in the present study in which older and younger adults completed an adaptive and individualized dual-task training program. The testing-the-limits approach was used [Lindenberger, U., & Baltes, P. B. (1995). Testing-the-limits and experimental simulation: Two methods to explicate the role of learning in development. *Human Development, 38*, 349–360.] in order to gain insight into how attentional control can be improved in older adults. Results indicated substantial improvement in overlapping task performance in both younger and older participants suggesting the availability of cognitive plasticity in both age groups. Improvement was equivalent among age groups in response speed and performance variability but larger in response accuracy for older adults. The results suggest that time-sharing skills can be substantially improved in older adults.

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1. Introduction

In the past few years a number of laboratory-based cognitive interventions have been designed in an attempt to improve specific aspects of cognitive functioning in seniors (see Kramer & Willis, 2003 for a recent review of this literature). In most cases, older and younger adults participated in extensive practice with laboratory-based paradigms that have been used to identify age-related deficits in memory, attention, problem solving, etc. A variety of results have been observed in these training studies. For example, in some studies, older and younger adults showed similar patterns of training benefits. This has been shown for instance in visual-search tasks in which participants must find a target among visual distractors. Both older and younger adults learned to perform visual search tasks at the same rate and both age groups achieved automatized search with extensive practice (Ho & Scialfa, 2002; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000). However, other studies have shown that younger adults, but not older adults, achieve automatized search in tasks that combine visual and memory search (Rogers, 1992; Rogers, Fisk, & Hertzog, 1994). In the memory domain, training programs using different mnemonic techniques have shown positive results in older adults, which suggests that they can benefit from memory training. However, the improvements are typically larger in younger adults (see Verhaeghen, Marcoen, & Goossens, 1992).

Interestingly, some studies have also reported larger training benefits for older than for younger adults. For example, a larger improvement in the performance of older compared to younger adults has been reported in a study involving extensive practice in multiple memory-search tasks (Baron & Mattila, 1989) and in dual-task performance (Kramer, Larish, Weber, & Bardell, 1999). A larger benefit of training in older than younger adults has also been observed in a task that requires preparing for a motor response (Bherer & Belleville, 2004). An interesting feature of these studies was the use of feedback and/or instruction conditions intended to assist the participants in developing effective strategies to better perform and coordinate the tasks. Providing participants with active feedback to encourage the development of effective strategies might be important for older adults to develop greater cognitive skills over the course of training. Indeed, this would appear to be particularly important given previous demonstrations of age-related deficits in metacognitive skills such as self-monitoring and information management (Dunlosky, Kubat-Silman, & Hertzog, 2003; Murphy, Schmitt, Caruso, & Sanders, 1987). Although this hypothesis is appealing, further studies are needed to disentangle the effect of the training protocol compared to mere practice on cognitive functioning in older adults.

Together the studies reviewed above clearly indicate that older adults can learn new skills. Thus, latent cognitive potential (i.e., cognitive reserve) exists even in old age and laboratory-based cognitive training may be an effective approach to develop this potential. However, given the small number of behavioral intervention and cognitive training studies that have been reported, the differences between the methodologies employed, and the fact that not all studies have produced positive results, conclusions remain speculative as to how cognitive vitality can be improved and maintained in old age. Many open questions remain with regard to the potential benefit of cognitive and behavioral interventions:

(a) What are the determinant factors of an efficient cognitive stimulation program? (b) What are the limits of cognitive reserve, or what is the range of cognitive plasticity and how and when is it reduced during aging? (c) Does the range of cognitive reserve vary among cognitive processes or domains (see Baltes & Kliegl, 1992)? Of course, further empirical studies would help to provide answers to these questions. Moreover, the use of a theoretical framework would also be of great value to categorize the existing findings and, perhaps more importantly, to predict the direction of cognitive change with regards to the type of intervention provided and the cognitive functions targeted.

One insightful way to examine an individual's latent potential or range of cognitive reserve is the testing-the-limits approach (Kliegl, Smith, & Baltes, 1989). The rationale of this approach is that detailed analyses of time compressed stimulating experiences will provide valuable information on the developmental mechanisms and range of medium and long-term developmental changes (Lindenberger & Baltes, 1995). The testing-the-limits approach aims to establish the boundaries of potential development or range of cognitive plasticity. To do so, cognitive performance is assessed under three conditions. First, *baseline level* of cognitive performance is assessed under standardized conditions. Then, performance is assessed in optimized conditions, designed to maximize motivation and performance, in order to measure *baseline reserve*, which refers to the current maximum potential of cognitive performance that can be achieved under idealized conditions (Kliegl et al., 1989). Finally, performance is assessed following cognitive training under optimized conditions as used to measure *baseline reserve*, in order to measure the maximum cognitive plasticity, or maximum latent potential of an individual. This is referred to as the *developmental reserve*. The testing-the-limits approach has been proposed to approximate the limits of developmental capacity and as such, as an efficient way to obtain a detailed picture of an individual's potential under "idealized" experiential conditions (Lindenberger & Baltes, 1995). Baltes and colleagues have argued that this approach can lead to identification of genuine age-related cognitive decline, rather than overestimate age-related differences due to unpracticed or non-optimized conditions of testing, assuming that age-related differences in reserve capacity are more accurately assessed near the limits of performance.

Application of the testing-the-limits approach to the memory domain (Baltes & Kliegl, 1992; Kliegl et al., 1989), using an intervention program with the Method of Loci to improve memory performance (this mnemonic strategy relies on the association of the to-be-remembered words to different well-known locations), indicated that both older and younger adults show cognitive reserve. However, the improvement was smaller in seniors than it was in young participants, suggesting reduced cognitive plasticity in older adults. The robustness of this finding led the authors to conclude that it expressed a fundamental neurobiological limit due to the aging process. Baltes and Kliegl (1992) also discussed their results in terms of cognitive domains, arguing that the reduced cognitive reserve in older adults may involve fluid intelligence, or mechanical aspects of cognition, sometimes referred to as process-based or control functions, and that this finding may not generalize to other cognitive domains. Although it is true that the memory processes assessed by the authors can be considered as mechanical aspects of cognitive functioning, the limited use of the testing-the-limits approach in the memory domain reduces the potential generalizability of this finding, even within the broad domain of fluid intelligence.

The goal of the present study is to assess potential cognitive plasticity in controlled attentional processes through the testing-the-limits approach. It has been frequently suggested that attentional control processes are particularly sensitive to age and that this may be related (McDowd & Shaw, 2000) to the substantial modifications observed in the frontal and prefrontal areas of the cerebral cortex during aging (Raz, 2000). Older adults' difficulty in performing concurrent tasks is one of the most well documented executive control deficits in the cognitive aging literature (Hartley, 1992; Kramer & Larish, 1996; McDowd & Shaw, 2000). In the past few years, an increasing number of studies have used the Psychological Refractory Period (PRP) paradigm to investigate age-related deficits in overlapping task performance (Allen, Lien, Murphy, Sanders, & McCann, 2002; Glass et al., 2000; Hartley, 2001; Hartley & Little, 1999). Typically this paradigm involves the performance of simple tasks with different stimulus onset asynchronies (SOA) (e.g., identifying a letter presented on a computer screen and discriminating between a high or low tone). The increased reaction time in the second task with decreasing SOA between the two tasks is used as a measure of dual-task costs. This measure along with the systematic manipulation of different task parameters has been employed to identify the cognitive processes that serve as the source of processing bottlenecks in dual-task performance (Pashler & Johnston, 1998).

Studies with older adults performing PRP tasks have led to diverging results with respect to the nature and source of age-related differences in dual-task costs. For instance, Hartley and Little (1999) reported larger dual-task costs in older adults compared to younger adults only when the two tasks required manual responses (see also Hartley, 2001). As a result of these findings, Hartley concluded that the age-related deficit observed in dual-tasks is localized to response generation processes. Glass et al. (2000) also reported larger dual-task costs (greater PRP effects) in older adults but concluded that the observed age-related performance deficit has three sources: general slowing, process-specific slowing and the use of a more cautious task-coordination strategy. However, Allen et al. (2002) observed equivalent magnitude PRP effects for younger and older adults even when the two tasks required manual responses. They concluded that parallel processing that enables efficient dual-task performance is relatively age-invariant, at least in some conditions. It thus seems that the source of age-related difference in dual-task performance could be linked to both, task-coordination strategies (Glass et al., 2000) and parallel processing (Allen et al., 2002). Moreover, both appear to develop as a result of training. Kramer et al. (1999) showed improved task-coordination strategies in dual tasks, and Allen et al. (2002) reported evidence of parallel processing with practice.

However, in a recent study, Maquestiaux, Hartley, and Bertsch (2004) observed that extensive practice did not allow parallel execution of two concurrent tasks in a PRP paradigm. It is thus possible that practice alone does not favor the development of efficient dual-task performance strategies. Indeed, such strategies may only develop when subjects are explicitly trained, through individualized adaptive feedback and task prioritization instructions, to concurrently perform multiple tasks (Kramer, Larish, & Strayer, 1995, 1999).

Thus the source of age-related differences in dual task performance remains unclear. Although the extensive research of Hartley and colleagues (1999, 2001) suggests that older adults often show larger dual-task deficits when both tasks require manual responses, exceptions have been noted (Allen et al., 2002), which suggests that older adults' dual-task deficits in some conditions could be partly explained by age-related differences in task coordination strategies (Glass et al., 2000). Moreover, Glass et al.'s (2000) proposal suggests that inducing efficient task-coordination strategies combined with practice may reduce age-related deficits in dual-task performance. In other words, using an efficient task-coordination strategy along with sufficient practice should help older adults to perform concurrent tasks. Rephrased in the testing-the-limits terminology described previously, age-related difficulty in performing concurrent tasks may be reduced near the limits of optimal performance (see also Kramer et al., 1999).

The present study investigates dual-task performance skills in older and younger adult participants in an experimental protocol that enables the assessment of the three levels of cognitive performance identified in the testing-the limits approach. Dual-task performance was assessed at the baseline level of performance, the baseline reserve (or the current level of latent potential) and the developmental reserve (or the maximum level of cognitive plasticity). This approach has the potential to elucidate the source(s) of age-related differences in the ability to coordinate the performance of multiple tasks and also to extend the application of the testing-the-limits methodology to other cognitive processes and abilities.

Recent studies suggest that age-related difference in executive control also lead to increased performance variability in older adults. In a recent report, West, Murphy, Armilio, Craik, and Stuss (2002) looked at different measures of performance variability in older and younger adults and observed that both between-person variability (diversity) and within-individual variability (dispersion) are greater in older individuals in tasks that put heavy demand on executive control. Moreover, while diversity was larger in older adults at initial testing only (at the 1st of 4 sessions) in the executive condition, age-related differences in within-person variability persisted despite four days of testing. In the context of cognitive training for attentional control, it is of interest to assess whether training in the testing-the-limits conditions will lead to reduced within person variability. In the present study, we explored age-related differences in between-person variability and within-person variability in the context of dual-task training. To our knowledge, the impact of training on response variability in older compared to younger adults has never been assessed within the context of the testing-the-limits approach.

2. Method

2.1. Participants

Twelve older and 12 younger adults participated in this study. Elderly participants were 5 women and 7 men living in the community, with a mean age of 70 years (SD = 7) and 16 (SD = 3.3) years of formal education. The young adult group was composed of 7 women and 5 men with a mean age of 20 years (SD = 1.4) and 14 (SD = 1.3) years of formal education. All participants reported good health and none of them had undergone major surgery in the year prior to testing. They also had no history of neurological disease and did not take any medications known to affect cognition. To exclude persons with dementia, older participants completed a modified extended version (Mayeux, Stern, Rosen, & Leventhal, 1981) of the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975). The modified MMSE examination did not show any indication of impaired cognitive abilities in the older group (mean score was 56, with a range of 53–57). Participants were screened for major perceptual impairment by completing questionnaires on auditory function and tests for near and far visual acuity. Participants also performed tests of general mental abilities (Kaufman brief intelligence test, Kaufman & Kaufman, 1990), psychomotor speed (box completion and digit copying), perceptual and mental speed (digit symbol, sequential complexity), short term and working memory (forward, backward and computation spans), as well as attention and executive functions (Stroop, Trail making A–B). Table 1

Table 1
Means and standard deviations for performance scores on the tests measuring IQ and other cognitive functions

Groups	Older	Younger
General mental ability		
Kaufman brief intelligence test	116.67 (9.7)	110.67 (5.0)
Psychomotor and mental speed		
Box completion (correct answers)	50.00 (13.1)	53.67 (13.4)
Digit copying (correct answers)	64.83 (13.0)	76.00 (9.5)
Digit symbol** (correct answers)	33.33 (8.4)	48.42 (7.2)
Sequential complexity (correct answers)	38.00 (8.7)	41.1 (11.6)
Sort-term and working memory		
Forward digit span	8.58 (3.0)	9.1 (1.7)
Backward digit span	6.67 (1.6)	6.42 (1.7)
Computation span*	2.58 (.8)	4.17 (1.5)
Attention and executive functions		
Stroop test** (correct answers)	35.17 (7.9)	52.17 (11.6)
Trail making test A** (time in s)	40.92 (16.3)	21.83 (3.1)
Trail making test B** (time in s)	96.08 (39)	44.08 (10.6)

Scores represent number of correct answers, number of correct sequence (span tests) and time to complete the tasks (in s).
* $p < .01$.
** $p < .001$.

presents the participants' performance on the psychometric tests in an effort to illustrate the characteristics of the participant populations on different perceptual and cognitive abilities.

2.2. Materials and procedure

Participants were asked to perform an auditory discrimination task and a visual identification task both separately and concurrently. The auditory task was to judge whether a tone was low or high in pitch (440 Hz vs. 990 Hz, duration = 250 ms). The visual task was to identify which of the two letters (B or C) was presented on the computer screen. The participant was comfortably seated on a chair in front of the computer. Viewing distance was approximately 45 cm. At this distance the letters subtended a vertical visual angle of 1.15° and a horizontal visual angle of .76°. Letters appeared in white on a black background. Auditory stimuli were presented via headphones equipped with a volume control so that volume level could be adjusted if needed, although it was set by default to a constant level.

A trial proceeded as follows: the participant started each trial by depressing the space bar. At this time, a fixation point (*) appeared in the middle of the screen for 500 ms. Then, the stimuli for one or both of the tasks were presented. Responses to the auditory and visual tasks were made with the index and middle finger of the right or the left hand. Response hand to task mapping was counterbalanced across subjects. The next trial was started with a depression of the space bar. A minimum interval of 500 ms separated subject responses and the beginning of a new trial.

At the beginning and the end of each session, participants completed two pure blocks of 20 single task trials (10 with each of the 2 tasks). Presentation order of the two blocks, one with the auditory task and one with the visual task was counterbalanced between sessions.

During these single-task blocks no feedback was provided except for a visual warning (yellow square appearing on the top left portion of the screen with the words "be careful") that appeared when participants committed two sequential errors.

The mixed blocks occurred between the presentations of the single-task blocks. During the mixed blocks subjects performed (a) the two tasks together and (b) just a single task. The order of the single-mixed trials and the dual-mixed trials within the mixed task blocks was unpredictable. The presentation of single-task trials within mixed blocks was intended to discourage the strategy of grouping the two responses on dual-task trials and also provided a measure of single-task performance in the mixed task blocks (in which subjects would need to be prepared to perform both of the tasks concurrently). Moreover, comparing single-task trials performed in the mixed block to single-task trials performed in the pure block provides a measure of the different processing requirements in the two blocks. That is, although the single task trials are equivalent in both the single and mixed blocks, subjects must be prepared to perform both tasks on any trial in the mixed blocks, which usually incurs RT cost. Heretofore, we will refer to this performance cost as a *task-set cost.* The difference in performance between the dual-task trials and single-task trials in the mixed blocks provides a measure of the processing necessary to perceive multiple stimuli and coordinate the execution of two responses. The associated RT cost will be referred to as a *dual-task cost.* Separately estimating task-set and dual-task costs will allow to assess the effect of training in preparing for and performing multiple tasks, within the context of the testing-the-limits approach. Age-related differences in preparing to respond to multiple as compared to a single task have been observed in task-switching studies (Kray & Lindenberger, 2000; Mayr, 2001).

At each trial in the mixed-block, the fixation point was followed by a tone, a letter or both stimuli at the same time. The mixed-blocks were composed of 40 single-task trials (20 from visual and 20 from the auditory task) and 40 dual-task trials (10 with each of the 4 stimulus combinations). The first session was used to establish the baseline level of performance. This session involved 2 single-task blocks, 2 mixed-task blocks and then another 2 single-task blocks. In this session, no feedback on the speed of performance was provided and the instruction was to complete the two tasks at the same time as fast and accurately as possible.

In the next session, participants started the training program. The participants completed five training sessions that differed from the pre-training session in several ways. First, the participants completed 2 single task blocks (20 trials in each block) followed by 8 mixed-blocks of 80 trials, in each training session. The session ended with two single task blocks of 20 trials each. Thus, at the end of each training session, the participants had completed 80 single-task trials in the single task blocks (40 in each task), 320 (40×8 blocks) single-task trials in the mixed-task blocks and 320 (40×8) dual-task trials in the mixed-task blocks. After 5 training sessions, participants had completed a total of 400 single-task trials in single-task blocks, 1600 single-task trials in the mixed-task blocks and 1600 dual-task trials in the mixed-blocks. Second, during the mixed-task blocks, instructions were provided to induce different prioritization strategies. In 3 blocks in each session subjects were instructed to assign the auditory task the highest priority and to respond to the tone first. In another 3 blocks in each session subjects were instructed to assign the visual task the highest priority and to respond to the letter first. Finally, in 2 blocks per session subjects were instructed to treat the tasks to be of equivalent priority. Training with variable priority instruction has been successfully used in the past to assist individuals in the development of efficient multi-task processing strategies (Gopher, 1982, 1993; Gopher, Armony, & Greenshpan, 2000; Kramer et al., 1995; Kramer et al., 1999). Third, the blocks also differed as to whether, and if so which of the stimuli for the auditory and visual tasks appeared first. In the three blocks in which the auditory task was prioritized, the tone preceded the letter by 200 ms in one block, followed the letter by 200 ms in another block or the tone and the letter appeared simultaneously. Similarly, when the letter was prioritized the letter appeared prior to the tone in one block, followed the tone in another block and was presented simultaneously with the tone in a third block. Each training session was composed of 8 mixed-blocks that differed on the basis of conditions of SOA and task priority. Block presentation was randomized within a training session.

During the mixed-blocks in the training sessions, feedback indicators were presented continuously on a histogram in the top left portion of the screen depicting performance (speed) on the dual-task trials. The histogram contained two bars, one bar for each task. The left bar showed performance in the task performed with the left hand and the right bar showed the task performed with the right hand. The bars indicated the mean RT for each task in the previous 5 trials for the dual-task trials only. The bars appeared in red and changed to yellow and then green to indicate progressively better (faster) performance. Fig. 1 shows an example of the screen display as it appeared to the subject during a mixed-block.

A line on the top of the histogram showed the criterion for good performance, based on a percentile of the response distribution of the single-task trials during the mixed-block in each of the sessions. The criterion of good performance was continuously updated on an individual basis as the session evolved and the response distribution of the single-task trials changed. Moreover, it varied according to the priority instructions. If the instruction indicated prioritizing one task, the criterion for good performance on the prioritized task was the 50th percentile (the median) of the RT distribution for that task when it was performed in the previous single-task trials during the whole mixed block. The non-prioritized task was to be performed at the 75th percentile of the RT distribution for that task when it was last performed in single-task trials. When instructions indicated equal emphasis for both tasks, the criterion of good performance was based on the 63rd percentile of the RT distributions of each of the tasks when last performed in the single task trials. These instructions were individualized and adaptive since they depended on the individual subject's performance. Furthermore, the instructions were used to motivate the subjects to continuously strive for improved performance (Baron & Mattila, 1989; Kramer et al., 1995; Kramer et al., 1999).

2.3. Mapping experimental conditions to critical conditions in the testing-the-limits procedure

The data from the different training conditions (variable or fixed instructions) as well as from the different training sessions, and post-test assessment have been published elsewhere (Bherer et al., 2005). In the present report, only the conditions that enable the assessment of the effects of training on dual-task performance within the context of the testing-the-limits approach will be presented, with the exception of the baseline level of performance and the pure-single task trials, which are presented to express training effects on task-set cost. Thus, the data presented here that correspond to the testing-the-limits conditions have not been published elsewhere. In keeping with the testing-the-limits methodology we will focus our analyses, in the present study, on the three conditions of baseline

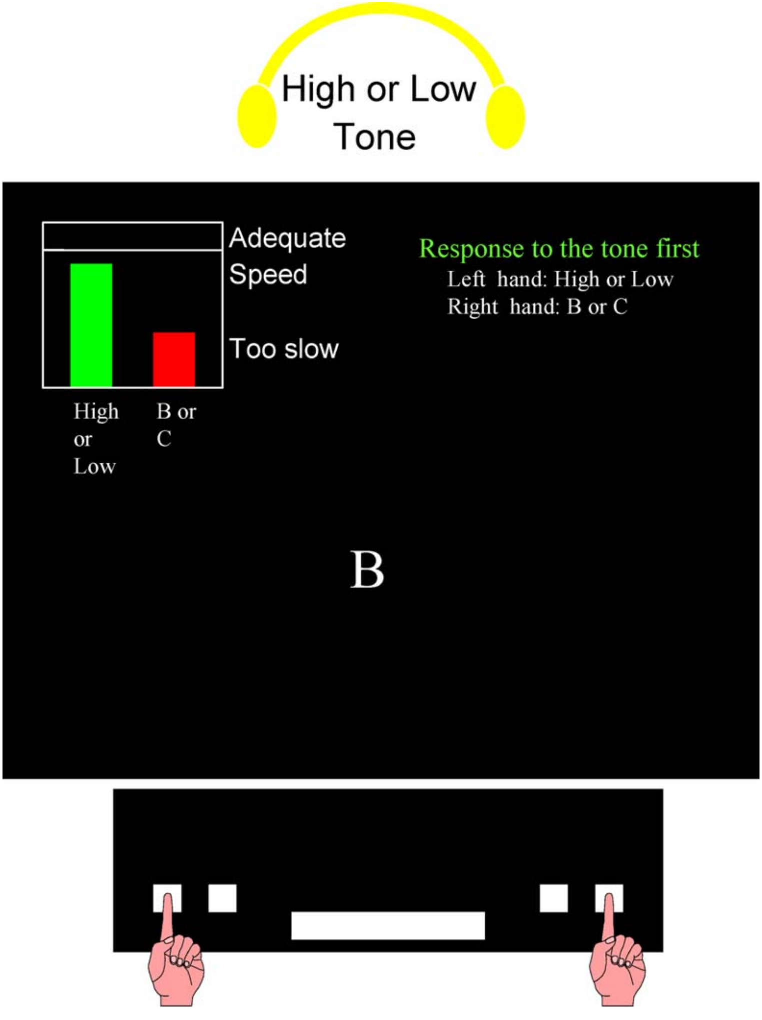

Fig. 1. Screen display as it appears to the subject during a mixed block. The bars in the histogram show the feedback for response speed in the dual-task trials, as a function of a response criteria based on the distribution of the single-task trials of the mixed-block (see text for details).

performance, baseline reserve and developmental reserve as a function of age and task. Measures of *baseline performance* were obtained for the single-pure and the single-mixed trials and the dual-mixed trials in both the auditory and visual tasks, in the pre-training session. In this session there was neither performance feedback nor instructions with regard to task prioritization. While performing in the dual-task condition, it was assumed that the optimal performance would be observed when the instruction and feedback required prioritizing one task over the other. To establish *baseline reserve*, RT and accuracy were thus computed for a given task only in the experimental blocks in which the task was prioritized (SOA between stimuli of the two tasks was 0 ms) and during which feedback emphasized this particular task. For instance, to establish baseline reserve in the Tone task, responses to the Tone task were computed for the block in which stimuli (the tone and the visual stimulus) were presented concurrently but the instruction indicated to respond to the Tone first. Similarly, responses to the visual task were compiled for the trials in which the instructions emphasized to respond to the visual task first. These conditions during the first training session served as a measure of baseline reserve. Finally, *developmental reserve* was assessed in the fifth session of training by computing RT and accuracy for a given task in the blocks that emphasized the task (same condition as baseline reserve but after 5 training sessions).

3. Results

The dependent variables of interest were mean response time (RT) and accuracy and measures of response time variability. Incorrect responses were not included in the analyses and trials were also rejected if RT was longer than 3000 ms or shorter than 100 ms. Statistical analyses of the data were performed with SPSS (SPSS Inc.), which provides adjusted alpha levels (Greenhouse-Geisser) for within-subject factors. An effect is reported significant here according to the adjusted alpha level when required, that is when Mauchly's test of sphericity was significant (SPSS, 1997). Effect sizes (η^2) are also reported.

3.1. Mean reaction time

Fig. 2 shows the mean RT of older and younger adults in both the auditory and the visual discrimination tasks during experimental blocks. Mean RTs are shown for the single pure trials, the single-mixed trials performed within the mixed block and the dual-mixed trials. Clearly, in both age groups RT became shorter from the *baseline level* of performance (i.e., the pre-training block) to the first session of training (*baseline reserve*), and improved again over the course of training (*developmental reserve*). The improvement in response speed appeared equivalent in both age groups, in both tasks and in single- and dual-task trials.

A mixed-design ANOVA was performed with Age group as the between subject factor and Task (auditory and visual), Session (baseline performance, baseline reserve, developmental reserve) and Trial type (single-pure, single-mixed and dual-mixed) as within subjects factors. The analyses indicated that older adults produced slower responses overall (934 ms) compared to younger adults (634 ms) as indicated by a main group difference, $F(1,22) = 22.19$, $p < .001$, $\eta^2 = .50$. Moreover, a significant main effect of Trial type was observed, $F(2,44) = 143.55$, $p < .001$, $\eta^2 = .87$. In fact, repeated-contrasts, which provide a comparison of RT difference between two consecutive levels of a repeated measure (SPSS, 1997) indicated that all participants responded faster in the single-pure trials (522 ms) compared to the single-mixed trials (811 ms), $F(1,22) = 103.76$, $p < .001$, $\eta^2 = .83$, and faster in the single-mixed compared to the dual-mixed trials (1019 ms), $F(1,22) = 148.95$, $p < .001$, $\eta^2 = .87$. The main effect of training session was also significant, $F(2,44) = 63.21$, $p < .001$, $\eta^2 = .74$. Overall performance improved significantly from the baseline assessment (909 ms) to baseline reserve (794 ms), $F(1,22) = 27.89$, $p < .001$, $\eta^2 = .56$, and even more so from the baseline reserve to developmental reserve (649 ms), $F(1,22) = 53.98$, $p < .001$, $\eta^2 = .71$.

Two interactions were significant. The Age × Trial type interaction, $F(2,44) = 7.72$, $p < .001$, $\eta^2 = .26$, was significant which suggests that the RT difference across trial types

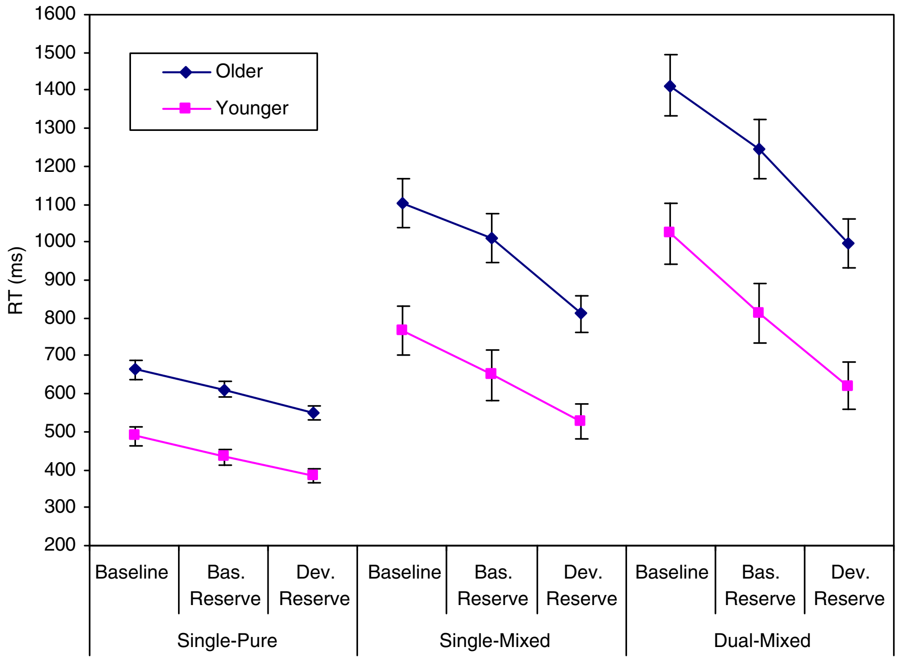

Fig. 2. Mean reaction time (ms) for older and younger adults as a function of conditions of testing (i.e., baseline level, baseline reserve and developmental reserve). Performance is shown for the three trial types; single-pure, single-mixed and dual-mixed trials.

varied between age groups. The difference between groups across trial types can be localized by computing task-set cost and dual-task cost shown in Fig. 3.

ANOVAs performed on these scores with Group as between subject factor and Task and Session as within subject factors, indicated that both task-set cost, $F(1,22) = 7.50$, $p < .01$, $\eta^2 = .25$, and dual-task cost, $F(1,22) = 4.33$, $p < .05$, $\eta^2 = .17$, were larger in older compared to younger participants. However, further analyses indicated that the Age × Trial type interaction was no longer significant once baseline speed of responses was controlled for, which suggests that age-related general slowing largely accounts for the group difference in task-set and dual-task costs in the present study.[1] The Session × Trial type interaction was also significant, $F(4,88) = 27.63$, $p < .001$, $\eta^2 = .56$, indicating that improvement across sessions differed among task-set and dual-task costs (see Fig. 3). In fact, results from the ANOVA performed on task-set cost indicated that although it tended to improve from baseline to baseline reserve, $F(1,22) = 3.71$, $p = .067$, $\eta^2 = .14$, significant improvement in task-set cost was significant only from baseline reserve to developmental reserve, $F(1,22) = 20.30$, $p < .001$, $\eta^2 = .48$. However, dual-task cost significantly improved from baseline to baseline reserve, $F(1,22) = 10.47$, $p < .01$, $\eta^2 = .32$, and again from baseline

[1] Age-related differences in general slowing are well documented in cognitive aging studies (Madden, 2001). In the present study, age-related slowing was controlled for by conducting ANCOVAs with baseline RT in the single pure trials averaged for the two single tasks in the first session. An interaction involving the Age group factor is considered significant only if it was also significant in the ANCOVA.

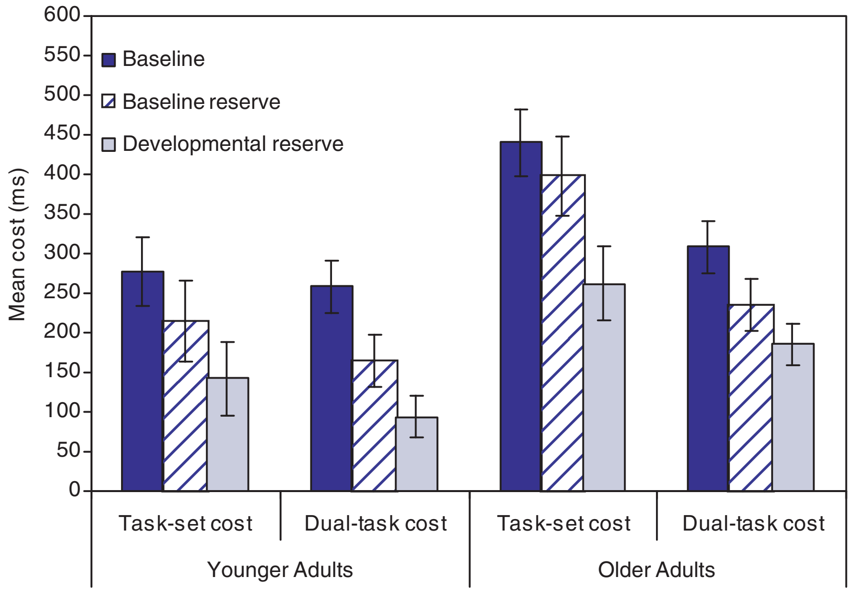

Fig. 3. Mean task-set cost and dual-task cost in older and younger adults as a function of conditions of testing (i.e., baseline level, baseline reserve and developmental reserve).

reserve to developmental reserve, $F(1,22) = 7.02$, $p < .02$, $\eta^2 = .240$. Finally, it is important to emphasize that no interaction involving Age group was observed, which suggests that older adults and younger adults showed the same pattern and the same magnitude of improvement over the course of training and that the differential improvement between task-set and dual-task costs was equivalent in both age groups.

3.2. Accuracy

Percentages of correct answers are shown in Fig. 4. Overall, older adults (86%) produced fewer accurate responses than young adults (95%), as indicated by a group main effect, $F(1,22) = 13.54$, $p < .001$, $\eta^2 = .38$. A main effect of session indicated that in both groups accuracy improved through training, $F(2,44) = 3.18$, $p < .05$, $\eta^2 = .13$. Moreover, the effect of trial type reached significance, $F(2,44) = 7.57$, $p < .001$, $\eta^2 = .26$. This was due to a significant decrease in accuracy from single-pure to single-mixed trials (significant task-set cost), $F(1,22) = 12.16$, $p < .01$, $\eta^2 = .36$. Although, this effect seems larger in older adults, the group difference in task-set cost was not significant, $F(1,22) = 3.47$, $p = .076$, $\eta^2 = .14$. Two interactions were significant. The Group × Session interaction was significant, $F(2,44) = 3.57$, $p < .05$, $\eta^2 = .13$. Repeated-contrasts indicated no age group difference in improvement between baseline and baseline reserve, $F(1,22) < 1$. However, older adults benefited from training to a greater extent than younger adults, from baseline reserve to developmental reserve, $F(1,22) = 4.57$, $p < .05$, $\eta^2 = .17$. Moreover, and as observed with RT data, the Session × Trial type interaction was significant, $F(4,88) = 3.16$, $p < .05$, $\eta^2 = .13$. This was due to a larger improvement in accuracy from the baseline reserve to developmental reserve in single-mixed compared to single-pure trial (improvement in task-set cost),

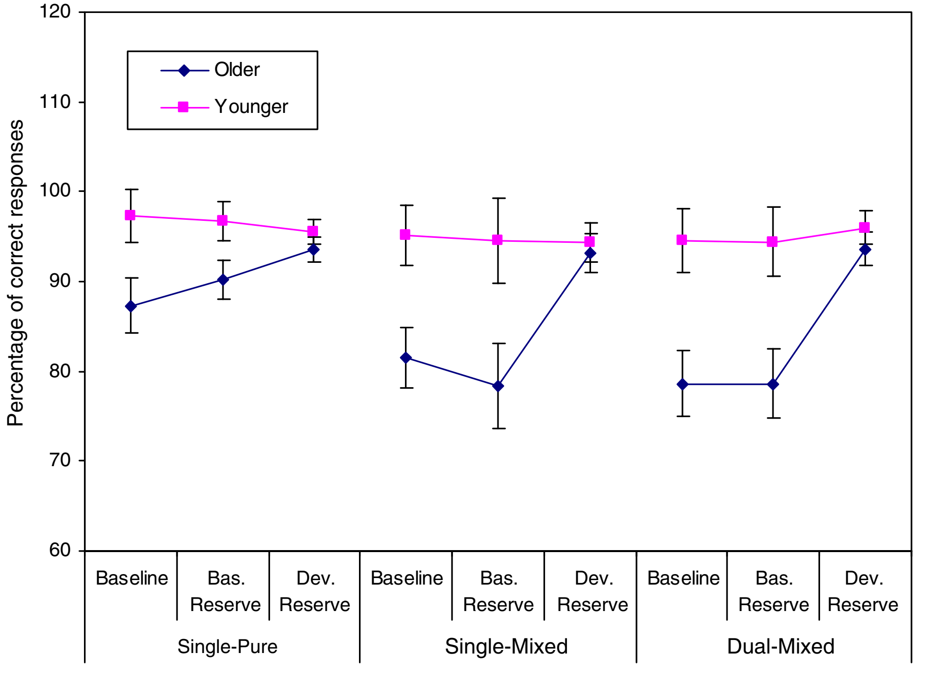

Fig. 4. Percentages of correct responses for older and younger adults as a function of conditions of testing (i.e., baseline level, baseline reserve and developmental reserve). Performance is shown for the three trial types; single-pure, single-mixed and dual-mixed trials.

$F(1,22) = 4.50$, $p < .05$, $\eta^2 = .17$, which was not observed when single-mixed trials are compared to dual-mixed trials (no change in dual-task cost in accuracy).

3.3. Between and within persons variability

To assess whether *between-person variability* was larger in older than younger adults and if it changed with training, we computed a Coefficient of Variability (see Table 2). This measure was preferred over standard deviation (SD) since it offers the advantage of taking into account the absolute mean (see Morse, 1993). This is important in the context of cognitive aging since in RT tasks slower responders often produce larger SDs. Thus, a larger SD could be the product of general slowing. Indeed, West et al. (2002) reported that in some studies an age-related difference in variability was explained by general slowing. In the present study, the group CV was computed using group SD deviation and group mean ($CV = SD/M * 100$) in the eighteen experimental conditions (2 Task × 3 Trial types × 3 Sessions) for both older and younger adults. As can be seen in Table 2, the results indicated that between-person variability was larger overall in older (24) than younger (19) adults. An ANOVA comparing CV of older and younger adults in the 18 experimental conditions showed that the group difference was significant, $F(1,34) = 4.25$, $p < .05$, $\eta^2 = .22$. We then assessed change in between-person variability as a function of trial types and session, separately for both older and younger adults. In both groups, variability depended of trial types, $F(2,15) = 5.65$, $p < .01$, $\eta^2 = .43$, in older adults and, $F(2,15) = 13.3$, $p < .001$, $\eta^2 = .64$, in

Table 2
Group Coefficient of Variability (CV = SD/mean * 100) and Individual Coefficient of Variability (ICV = ISD/mean * 100) as a function of trial types and sessions for both older and younger adults

Group	Trial types	Baseline level	Baseline reserve	Developmental reserve
Group Coefficient of Variability (CV)				
Older	Single-pure	16.31	16.23	16.32
	Single-mixed	26.20	30.74	28.98
	Dual-mixed	23.87	27.40	30.36
Younger	Single-pure	16.86	13.04	11.27
	Single-mixed	20.18	22.22	17.93
	Dual-mixed	22.44	26.87	21.31
Individual Coefficient of Variability (ICV)				
Older	Single-pure	38.17	40.87	30.83
	Single-mixed	36.68	32.22	28.54
	Dual-mixed	33.72	34.40	35.48
Younger	Single-pure	29.81	29.27	25.06
	Single-mixed	30.42	26.85	23.37
	Dual-mixed	35.36	35.91	31.32

In the absence of performance variability between task, data were pooled for the auditory and the visual tasks.

younger adults. Respectively for single-pure, single-mixed and dual-mixed trials, mean CV were 16, 29, 27 in older adults and 14, 20, 24 in younger adults. Repeated contrasts indicated that between-subjects variability was smaller in single-pure trials compared to single-mixed trials ($p < .05$, for both groups), whereas CV did not differ between single- and dual-task trials within the mixed block. Moreover, CV did not change as a function of training in both older and younger adults since there was no significant difference as a function of session.

Within-participants variability was measured by computing individual coefficients of variability (ICV = ISD/individual mean * 100), using individual standard deviation (ISD) computed for each participant in each experimental condition of interest. Table 2 shows the ICVs in each training session (Baseline performance, Baseline reserve, Developmental reserve) and for each trial types (single pure and mixed trials, and dual-mixed trials). An ANOVA performed on these data indicated that within-participant variability is larger in older adults (35) compared to younger adults (30), $F(1,22) = 6.54$, $p < .02$, $\eta^2 = .23$. Moreover, within-subject variability decreased with training as indicated by a main effect of session, $F(2,44) = 11.10$, $p < .001$, $\eta^2 = .34$. The improvement from Baseline performance (34) to Baseline reserve (33) was not significant, $F(1,22) < 1$, whereas improvement from Baseline reserve to Developmental reserve was significant, $F(1,22) = 15.96$, $p < .001$, $\eta^2 = .42$, reaching 29 in the last training session. A main effect of trial type, $F(2,44) = 7.53$, $p < .01$, $\eta^2 = .26$, showed that ICV differed according to trial types. In fact ICV was larger in dual-mixed trials (34) compared to single-mixed trials (30). The Group × Trial type interaction, $F(2,44) = 5.94$, $p < .01$, $\eta^2 = .21$, was significant. This was due to a larger increase in ICV between dual-mixed and single-mixed trials in younger compared to older adults, $F(1,22) = 6.17$, $p < .02$, $\eta^2 = .22$.

4. Discussion

The goal of the present study was to assess whether and if so to what extent, overlapping task performance can be improved through training in older and younger adults. A laboratory based training experiment was designed in which continuous, individualized adaptive feedback and priority instructions were utilized in an effort to improve dual-task performance. The results indicated that both older and younger adults improved their performance over the course of training in response speed, response variability and accuracy. Considered within the testing-the-limits approach, it was observed that dual-task performance improved in both age groups from the baseline level to the baseline reserve. This suggests that optimal conditions of performance had a beneficial effect for both older and younger adults. Moreover, improvement was even better after training, showing evidence of developmental reserve in both age groups. Mean reaction time measures indicated that this pattern of improvement was equivalent for older and younger adults. However, improvement in accuracy was larger for older adults compared to younger adults from baseline reserve to developmental reserve that is from the first to the last training session. This effect must be interpreted with caution, however, since accuracy was quite close to ceiling, particularly for the younger adults throughout training. On the other hand, the fact that old and young showed equivalent improvements in response speed and variability while the old also showed substantial improvements in accuracy (such that developmental reserve accuracy was equivalent in old and young participants) attests that latent cognitive reserves exist in dual-task processing even in old age.

With regard to performance variability, an age-related difference was observed in both between- and within-persons variability indexes, with older adults showing more variability than younger adults, in line with previous studies (Morse, 1993; West et al., 2002). West et al. (2002) observed that age-related differences in between-person variability were only significant at the first experimental session, while age-related differences in within-person variability were maintained throughout the practice. In the present study, the age-related difference in between- and within-person variability did not change with training, and within-person variability decreased as a function of training in both age groups. Moreover, variability in performance increased in dual-task conditions, between-person variability being larger in single-mixed compared to single-pure trials, and within-person variability being larger when two responses must be coordinated in the mixed block (dual compared to single-mixed trials). This finding is also consistent with West et al.'s (2002) proposal that performance variability tends to be larger in task conditions that put heavy demand on executive control, as when two tasks are performed in the mixed-block of the present study. However, we did not observe larger age-related differences in variability (between- or within-persons) in task conditions that tap attentional control, which would have led to an increased variability in older adults within the mixed-blocks.

The results reported here also seem consistent with the increased entropy model of aging. According to this view, neural loss associated with aging increases neural noise and produces neural entropy, which leads to increased performance variability (Allen, Kaufman, Smith, & Propper, 1998). Age-related general slowing could be viewed as a by-product of greater entropy in older adults. An important finding in the present study was that performance variability decreased with training in both older and younger adults, which suggests that cognitive training may lead to reduce entropy across the adult lifespan.

The present study showed equivalent dual-task costs in older and younger adults. That is the difference in performance between single and dual-task trials did not differ as a function of age (once general slowing is control for). This pattern of results is consistent with recent findings using a somewhat different experimental method (Allen et al., 2002). With a classical PRP paradigm, Allen et al. (2002) observed an equivalent PRP effect in older and younger adults using a shape discrimination task combined with a lexical-decision task. As in the present study, Allen et al. also combined two manual response tasks. These data are, at first glance, inconsistent with Hartley's (2001) proposal of a specific age-related deficit when overlapping tasks require similar motor responses.

A potential explanation for this apparent discrepancy comes from Glass et al.'s (2000) observations. They suggested that age-related differences in dual-task performance could result from three different sources: generalized slowing, process specific slowing and differences in task-coordination strategy. Given the high degree of similarity between the experimental conditions used in the present study and the conditions used in Hartley's (2001) study, it is reasonable to rule out general slowing and process-specific slowing as potential explanations for the different patterns of results. However, the third source of age-related differences in dual-task identified by Glass et al. (2000) is likely to play a major role here since the task instructions differed substantially across studies. In fact, Hartley used a classical PRP approach in which one task is always completed first and in which an interval (SOA) of 50–1000 ms separated the two tasks. This is known to favor serial processing of the two tasks. In the present study, the instruction at the baseline assessment was to complete the two tasks at the same time without prioritizing one over the other. Moreover, both at the baseline assessment and during training, stimuli for the two tasks were presented at the same time (SOA = 0 ms). These conditions, along with the training instructions and feedback used in the present study might favor more flexible and partially overlapping processing of the two tasks, leading to equivalent dual-task costs in both age groups.

It was also observed in the present study that task-set cost significantly improved with training. Task-set cost has often been attributed to the capacity to hold stimuli and responses alternative in memory. Thus, improvement in task-set cost can be viewed as an improvement in working memory capacity, and suggests that older adults are able to reduce the burden of task requirements through training. In our study, both task-set cost and dual-task cost improved through training. It may thus be the case that, along with improvement in task coordination strategy (evidenced by dual-task cost improvement), reduced resources and possibly increased parallel processing of the two tasks (evidenced by task-set cost improvement) also contribute to improvement in concurrent task performance in older adults.

Although further studies are needed to better understand how (and when) age impairs the ability to perform concurrent tasks or rapidly switch between different tasks, the results reported here, along with previous training studies (e.g., Baron & Mattila, 1989; Kramer et al., 1995, 1999; Sit & Fisk, 1999), suggest that the ability to time share can be substantially improved in older adults. Furthermore, we believe that the testing-the-limits approach (Kliegl et al., 1989) should play a central role in addressing these questions—since it enables the examination of dual-task costs in an objective and standardized manner by which the comparison of training effectiveness across different procedures can be investigated. Within the context of the testing-the-limits approach, our results suggest that age does not necessarily reduce the range of cognitive plasticity that can be achieved after substantial training.

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