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Plasticity of Executive Functioning in Young and Older Adults: Immediate Training Gains, Transfer, and Long-Term Maintenance

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The authors investigated immediate training gains, transfer effects, and 18-month maintenance after 5 weeks of computer-based training in updating of information in working memory in young and older subjects. Trained young and older adults improved significantly more than controls on the criterion task (letter memory), and these gains were maintained 18 months later. Transfer effects were in general limited and restricted to the young participants, who showed transfer to an untrained task that required updating (3-back). The findings demonstrate substantial and durable plasticity of executive functioning across adulthood and old age, although there appear to be age-related constraints in the ability to generalize the acquired updating skill.

Keywords: executive training, age-related differences, plasticity, maintenance, transfer

There is a wealth of evidence that normal aging is associated with progressive functional loss in many cognitive domains, including mental speed, episodic memory, and executive functions (Craik & Salthouse, 1999; Hoyer & Verhaeghen, 2006). This fact has prompted an interest in questions related to the modifiability of cognitive functions across the life span, for example, to delineate training regimens with the potential to maintain or enhance cognitive performance in old age (Bherer et al., 2005; Greenwood, 2007; Kramer & Willis, 2003). Knowledge pertaining to one aspect of cognitive plasticity—the ability to improve performance after extensive training—in young and older subjects provides insights into the potential and boundaries for new learning across the adult life span and is therefore of both theoretical and practical importance (Baltes & Singer, 2001).

Previous cognitive training research in adulthood and old age has focused extensively on strategies aimed at improving episodic memory using techniques such as the method of loci and the face–name mnemonic (Stigsdotter Neely, 2000; Verhaeghen, 2000). Results have convincingly demonstrated that episodic memory can be improved across the life span, from middle childhood (Brehmer, Li, Müller, von Oertzen, & Lindenberger, 2007) through old age (Jones et al., 2006) into old-old age (Singer, Lindenberger, & Baltes, 2003). Cognitive intervention research has also addressed a plethora of other functions, such as fluid intelligence (Baltes & Willis, 1982), mental speed (Ball, Beard, Roenker, Miller, & Ball, 1988; Ball & Owsley, 2000), and aspects of executive functions, such as attentional control (Bherer et al., 2006; Kramer, Hahn, & Gopher, 1999), inhibition (Davidson, Zacks, & Williams, 2003), and task shifting (Kray & Epplinger, 2006). The results from these studies have also shown positive effects after training on the targeted cognitive skill for both young and older adults. However, the pattern of improvements for young and older adults has differed considerably across studies, with some studies reporting parallel gains across age (Kramer et al., 1999) and others more pronounced gains for older compared with young adults (Bherer et al., 2005). Yet the most frequently observed pattern has been that of greater improvement for young than for older adults (Baltes & Kliegl, 1992; Hoyer & Verhaeghen, 2006; Jones et al., 2006; Kray & Epplinger, 2006; Nyberg et al., 2003). Nonetheless, even in the studies showing the latter outcome pattern, older adults typically benefited to some degree from training, suggesting that cognitive plasticity is characteristic of both young and older adults, and focused cognitive training protocols may thus be an effective approach to realize this potential.

Theoretical models of cognitive aging have been influenced by the frontal lobe hypothesis, which assumes that age-related cognitive decline largely reflects age-related changes in the frontal lobes (Dempster, 1992; Duncan, 1995; Raz, 2000; West, 1996). Executive functions are commonly ascribed to the frontal lobes (Smith & Jonides, 1999), and several studies have shown that these functions are negatively affected in later adulthood (Kray & Lindenberger, 2000; Salthouse & Babcock, 1991; Van der Linden, Brédart, & Beerten, 1994). Executive functions broadly encompass

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cognitive control processes responsible for the regulation of behavioral activities (Miller & Cohen, 2001). Furthermore, executive functions underlie general intelligence and are imperative to everyday functioning (Dujardin et al., 2004). Given the frontal lobe hypothesis of aging and the importance of executive functioning in everyday cognitive activities, it is striking that relatively little interest has been paid to the potential modifiability of these functions. The purpose of the present study was to contribute to this field of research by examining the capacity to improve executive functioning (i.e., promoting executive plasticity) in young and older healthy adults. The present study is an extension of a previous functional magnetic resonance imaging (fMRI) study (Dahlin, Stigsdotter Neely, Larsson, Bäckman, & Nyberg, 2008) in which we investigated the neural basis for transfer effects. Here we report data from a larger sample using a broader battery of transfer tasks. Specifically, whereas the fMRI study included only two transfer tasks, the current study report data from nine additional tasks that measured episodic and semantic long-term memory, working memory, reasoning ability, and speed of processing. Moreover, in the current report we address the issue of durability of training effects and report data from an 18-month follow-up study session. Our work was guided by a model of executive functions proposed by Miyake et al. (2000). This model highlights three separate but related executive functions: shifting, inhibition, and updating. We focused on the updating function, which requires continuously modifying the content of working memory according to incoming information. This choice was governed by the following considerations. First, updating is an integral part of working memory (Smith & Jonides, 1999) and has been proposed to be one of the more important executive functions in everyday life (Channon, 2004; Collette & Van der Linden, 2002). It is well established that older adults perform more poorly than young adults on tests of working memory (Baudouin, Vanneste, Pouthas, & Isingrini, 2006). One explanation offered to account for these deficits is impaired monitoring and updating functions (Hartman, Dumas, & Nielsen, 2001). Furthermore, working memory capacity has been shown to be important to cognitive plasticity (Verhaeghen, 2000). Finally, among the three executive functions included in the Miyake et al. model, updating was found to be most closely related to intelligence (Friedman et al., 2006). In view of these facts, updating seemed like a prime candidate to be addressed in training studies.

An unfortunate characteristic of previous cognitive intervention research is the scarcity of studies addressing long-term maintenance and transfer effects following training. Thus, in addition to investigating potential differences in the modifiability of updating performance in young and older adults, we were interested in examining the stability of updating performance across an extensive period, as well as the generalizability of improved updating abilities to a wide array of cognitive tasks not targeted in training.

A few previous studies investigated long-term maintenance following training in young and older participants. For example, a study using a dual-task paradigm (Kramer et al., 1999) showed maintenance of improved switch costs 2 months after completion of training for both young and older adults. Further, it has consistently been shown in earlier mnemonic-training studies with older adults that encoding and retrieval skills may be maintained years after completion of training (Stigsdotter Neely & Bäckman, 1993; Willis et al., 2006). Long-term effects of mnemonic training have also been demonstrated in early Alzheimer's disease patients (Clare, Wilson, Carter, Roth, & Hodges, 2002). On the basis of these findings, we expected to find maintenance of improved updating performance in both young and older adults 18 months after completion of the training phase.

Transfer of acquired skills is at the heart of learning and perhaps the ultimate goal of cognitive intervention. Despite the relevance of this issue, it still remains poorly studied, and most research indicates rather limited transfer effects in older adults (Ball et al., 2002; Derwinger, Stigsdotter Neely, Persson, Hill, & Bäckman, 2003; Edwards et al., 2002; Rebok, Carlson, & Langbaum, 2007; Stigsdotter Neely & Bäckman, 1993; for examples of positive transfer effects in older adults, see Ball & Owsley, 2000; Jennings, Webster, Kleykamp, & Dagenbach, 2005). In a recent study, transfer effects were examined following dual-task training (Bherer et al., 2005). One transfer task was used, which differed from the trained task only in terms of the specific items included. The results revealed improved performance in the transfer task for both young and older adults, showing that the training effect was not tied to specific items. Transfer effects have also been found following in working memory training in young adults (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Klingberg, Forssberg, & Westerberg, 2002; Westerberg & Klingberg, 2007). In a study by Klingberg, Forssberg, and Westerberg (2002), increased performance after training was seen for both trained and nontrained visuospatial working memory tasks, as well as for a "far" transfer test (i.e., a reasoning task that did not closely overlap with the criterion task in terms of procedures and underlying processes). Moreover, Jaeggi, Buschkuehl, Jonides, and Perrig (2008) found transfer to untrained tests of fluid intelligence after training on *n*-back working memory tasks.

In the present study, we used an extensive battery of tests to examine transfer of updating training to nontrained tasks taxing perceptual speed, episodic and semantic memory, reasoning, and working memory. The rationale for selecting these cognitive domains was that the included transfer tasks taxed functions critical for everyday life, and the selection was also based on a wish to be compatible with previous training research. In line with the long-held view that a key ingredient for the occurrence of generalization is that the transfer task taps similar cognitive operations as the trained task (Thorndike & Woodworth, 1901), we expected "near" transfer to tasks tapping overlapping processes as the trained task (i.e., tasks taxing updating). The durability of transfer effects was examined at the subsequent maintenance session.

Specifically, on the basis of previous empirical findings on the effects of cognitive training in adulthood and old age, we addressed the following issues. First, at both the group and the individual level, we examined whether young and older adults would improve their updating performance after updating training. Of main interest was whether older adults would show evidence of executive plasticity at all. In addition, we conducted age comparison of the relative training gains based on absolute scores. Furthermore, we investigated whether the participants maintained performance gains on the criterion task 18 months after completion of training. Finally, we examined whether updating training generalized to untrained tasks, some of which involved an updating component and others that did not tax this executive process.

Method

Participants

Thirty-two older and 32 young adults participated in this study. Of the older adults, 16 were randomly assigned to a training group and 16 to a control group. Of the young adults, 17 were assigned to a training group and 15 to a control group. The young participants were recruited through e-mail to students at Umeå University. The older participants were recruited through advertisements in one of the larger local newspapers. All participants who completed the study received 1,000 SEK (approximately $160).

Six young and 3 older participants dropped out; hence, the final sample consisted of 15 young and 13 older adults who received training and 11 young and 16 older participants serving as controls. Analyses on background characteristics revealed no differences between those remaining in the study and the dropouts within the respective age group. Owing to technical problems, we lost pretest and Posttest 1 data in the letter memory criterion task and the 3-back task from 2 participants in the older adult training group. Hence, the analyses of these tasks were based on 11 trained older adults. As can be seen in Table 1, the training and control participants in each age group did not differ significantly ($p > .05$) with respect to age, years of education, depression (Beck & Steer, 1996), verbal ability (Dureman & Sälde, 1959), mental status (Folstein, Folstein, & McHugh, 1975), attention and mental speed functions measured by Trail Making Tests A and B (Lezak, 1983), and pattern comparison (Salthouse & Babcock, 1991). Furthermore, all participants reported being in good physical and mental health, not color blind, and right-handed.

Pretest and Posttest 1 data from the letter memory criterion task and the *n*-back transfer task from 22 of the young and 19 of the older participants were reported in a previous report that focused on the findings from an fMRI study (Dahlin et al., 2008). The reason for reporting pretest and Posttest 1 results from these tasks in the current study is that more controls have been added. At the 18-month Posttest 2 session, all of the older participants who received training and 11 of the 15 trained young participants returned for Posttest 2 testing. The 4 young dropouts had moved from the community at the time of Posttest 2. For the control groups, 7 young and 7 older persons were invited back to participate in the 18-month follow-up. The remaining controls were not invited back for practical reasons.

The study was approved by Umeå University's ethics committee. All participants were informed about the purpose of the investigation and their right to terminate participation at any point in time, and gave written informed consent to participate.

Design and Procedure

All participants were individually tested at pretest, Posttest 1 (immediately after completing the training program), and Posttest 2 (18 months after completion of training). The participants receiving training were invited to participate in 15 sessions during a period of 5 weeks. Each session lasted for 45 min (three sessions per week), and participants trained in groups of four. The updating training was computer based, a format that has been shown to be beneficial to both young and older persons (Klingberg et al., 2005; Rasmusson, Rebok, Bylsma, & Brandt, 1999). The training program is described in detail in the next section.

Training Sessions

A training session consisted of practice on the criterion task and five training tasks, all of which require updating. We used an adaptive regime to ensure that the tasks remained cognitively challenging throughout the training period.

Criterion task. The letter memory task (Miyake et al., 2000; Morris & Jones, 1990) was used as criterion task. This task involved 10 lists of the following lengths: 7, 7, 9, 9, 11, 13, 9, 5, 13, and 15 items. Each list consisted of serially presented letters (*A–D*, 2 s per letter), and participants were asked to monitor and update the four last presented letters during the list presentation. When the list ended, participants were asked to recall and type in correct order of the four last presented letters as quickly as possible using their right hand: index finger = *A*; middle finger = *B*; ring finger = *C*; pinky finger = *D*. The dependent measure was the number of correctly recalled four-letter sequences (maximum score = 10). This task was administered at pretest, first in each

Table 1
Mean Subject Characteristics

Characteristic	Young trained	Young control	Old trained	Old control
Women/men (*n*)	8/7	4/7	7/6	11/5
Age (years)	23.67 (2.92)	24.09 (2.12)	68.38 (1.66)	68.25 (1.73)
Education (years)	13.40 (1.40)	13.82 (1.87)	14.50 (4.07)	12.03 (3.00)
Depression[a]	3.40 (3.27)	3.64 (3.26)	3.46 (3.23)	6.31 (4.41)
Verbal ability[b]	22.67 (2.61)	22.09 (3.62)	22.38 (5.01)	23.25 (3.84)
Mental status[c]	29.00 (0.93)	29.18 (0.87)	28.69 (1.03)	28.81 (0.66)
Trail Making Test A[d]	25.57 (7.74)	27.79 (10.55)	41.98 (12.59)	43.09 (12.92)
Trail Making Test B[d]	61.92 (16.94)	49.06 (17.13)	97.07 (30.55)	95.74 (26.05)
Pattern comparison[e]	21.27 (2.74)	21.45 (4.16)	15.38 (1.79)	13.97 (2.25)

Note. Standard deviations are given in parentheses.
[a] Beck Depression Inventory (Beck & Steer, 1996). [b] SRB1 (Dureman & Sälde, 1959; maximum score = 30). [c] Mini-Mental State Examination (Folstein et al., 1975). [d] Trail Making Tests A and B (Lezak, 1983). [e] Pattern comparison (Salthouse & Babcock, 1991).

training session, and at Posttest 1 and Posttest 2. Some of the participants did this task in an fMRI scanner at pretest and Posttest 1. The same version of the task was used inside and outside the scanner, and no differences in performance were found between fMRI and non-fMRI participants ($p > .05$).

Training tasks. Four of the practice tasks were similar in format to the criterion task and required updating of single items (numbers, letters, colors, and spatial locations). For each of these tasks, five lists of items were randomly presented and the task was to recall the four last presented items in correct order. Each item was presented for 2 s. Two dependent measures were used: number of correctly recalled four-item sequences (maximum score = 5) and number of correctly recalled items (maximum score = 20). To manipulate difficulty level, list length was varied as follows: low level = 4–7 items; medium level = 6–11 items; high level = 5–15 items, where the lower levels were considered less cognitively taxing. Performance was monitored, and level of difficulty was adjusted when participants scored 80% correctly recalled items on the letter-training task (i.e., 16 letters or more correct). All participants started at the low level, and all had reached the most difficult level at Week 5.

The remaining training task was the keep-track task (Miyake et al., 2000; Yntema, 1963). This task required updating, categorization, and association. In this task, three trials of 15 words per trial from various semantic categories were presented serially at 2.0 s per word in random order and participants were instructed to mentally place the words into categories (animals, clothes, countries, relatives, sports, professions) indicated by boxes at the bottom of the screen. Participants had to update the content continuously and remember the last presented word in each category at the end of the presentation. They responded by typing the last presented word under each category box at the end of each trial. Difficulty level was manipulated by varying the number of categories presented, with three (low), four (medium), or five (high) target categories, respectively. During each training session, participants performed this task twice: first three trials with five target categories and then with an adjusted difficulty level.

Materials and Testing

To assess potential transfer effects of training, a battery of cognitive tests was administrated at pretest, Posttest 1, and Posttest 2. The tests included five measured cognitive domains: perceptual speed, working memory, episodic memory, verbal fluency, and reasoning.

Perceptual speed. The task used to assess aspects of mental speed was digit symbol substitution from the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1987). The task was administered according to standard procedures: Participants were instructed to copy as many symbols as possible during 90 s into empty boxes according to associations specified in a coding key. The key consisted of nine geometric symbols numbered from 1 to 9. Number of correct symbols completed was used as outcome measure.

Working memory. Four tasks were used to assess different aspects of working memory. In the first task, computation span (Salthouse & Babcock, 1991), participants solved arithmetic problems while holding the final digit from each problem in memory for later recall. The number of arithmetic problems increased with one at each span level. Three trials were presented at each span level, and the outcome measure was the highest span level reached when two out of three trials were correctly solved. Two versions of the task were used. Version 1 was administered at pretest and Posttest 2, and Version 2 was administered at Posttest 1. Digit span forward and backward from the Wechsler Adult Intelligence Scale were also used and administered according to standard procedures. Here digits were presented at a rate of 1 s per digit and participants were instructed to repeat the digits in order of the presentation (forward) or in reverse order (backward). Two trials for each span level were presented. The score used corresponded to the span level for which at least one of two trials was correctly repeated. Three parallel versions of this task were used, one at pretest, one at Posttest 1, and one at Posttest 2. The final working memory task was the *n*-back task (Cohen et al., 1993). In this task, participants were asked to indicate whether each number in a list matched a number (1–9) that occurred one, two, or three numbers back. To respond, the participants used their right hand (index finger = “yes,” middle finger = “no”). Number of correct “yes” responses was used as dependent measure. The maximum score was 36. Some of the participants did this task in an fMRI scanner at pretest and Posttest 1, but no differences in performance were found between the fMRI and non-fMRI participants ($p > .05$).

Episodic memory. Two in-house developed tasks were used to assess aspects of episodic memory. In recall of concrete nouns, participants were asked to freely recall as many words as possible after studying a list of 18 serially presented nouns in which each noun was presented for 5 s. The test was administered according to Buschke’s selective reminding procedure (Buschke, 1973): On the first trial, all to-be-remembered items were presented. On the two subsequent learning trials, only those items that were not recalled on the previous trial were orally re-presented and participants were asked to recall both reminded and nonreminded items. Number of correctly recalled items on each of the three trials was used to index performance. The second episodic memory task involved paired-associate learning. Here participants were asked to associate two nouns to each other. After studying a serially presented list of 18 pairs of nouns presented for 5 s each, the participants were asked to recall the last noun in the pair when given the first noun as a cue. The cues were not presented in the same order as at study. Half the presented pairs were weakly associated (e.g., sky–movie) and half were strongly associated (e.g., cat–dog). Number of correctly recalled word pairs was used as the dependent measure. In both episodic memory tasks, three versions were used. The two first versions were counterbalanced between pretest and Posttest 1 and the third version was used at Posttest 2.

Verbal fluency. To assess verbal fluency, a Swedish version of the Controlled Oral Word Association Test (Benton & Hamsher, 1989) was used. In letter fluency, participants were asked to write down as many words as possible beginning with the letters *F*, *A*, and *S* during 90 s, with the exception of proper names or places. In category fluency, they were asked to produce as many words as possible during 90 s belonging to different categories: provisions, the names of animals beginning with the letter *S*, and professions beginning with the letter *B*. Number of correct words generated was used as outcome measure.

Reasoning. To assess nonverbal intelligence, Raven’s Advanced Progressive Matrices (Raven, Raven, & Court, 1998) was used. This test is based on perceptual analogies presented in the form of two-dimensional pattern-matching matrices. Participants selected from eight options the one that best fitted the missing section to complete the pattern. The task consisted of 36 patterns. Half the patterns were administered at pretest and the reminding half at Posttest 1 in a counterbalanced fashion. The half presented at pretest was also administered at Posttest 2. Number of correctly completed patterns during 20 min was used as the outcome measure. A practice block was administered before the test commenced for 5 min.

The cognitive tests were administered in the following order for all participants (tests marked with an asterisk were administered only at pretest to reduce testing time): (1) Mini-Mental State Examination;* (2) number copying;* (3) digit span forward and backward; (4) recall of concrete nouns; (5) digit symbol; (6) computation span; (7) letter fluency; (8) verbal ability;* (9) pattern comparison;* (10) 15-min break; (11) paired associates; (12) Trail Making Tests A and B;* (13) Raven's Advanced Progressive Matrices; (14) category fluency; (15) health questionnaire, Beck Depression Inventory, and demographic questionnaire;* (16) letter memory; and (17) *n*-back. The letter memory and *n*-back tasks were administered proximally 1 week after the other tasks.

Analyses

First, to separate true training gains from test–retest effects in untrained participants, we compared pre- and immediate posttraining scores for trained participants and controls on the criterion and transfer tasks. This was done within each age group separately. Second, on tasks for which significant training effects were observed, we directly assessed age effects by comparing trained young and older participants (i.e., controls were not included in these latter analyses). Finally, analyses of long-term maintenance at the second posttest were restricted to those tasks that showed true training gains in the first set of analyses.

Results

Immediate Training Effects (Criterion Task)

To test for training-related gains following updating training in young and older adults, 2 (Group: trained, control) × 2 (Session: pretest, Posttest 1) analyses of variance (ANOVAs) with repeated measures on the last factor were performed on the criterion task (letter memory) for the young and older adult group, respectively.

Training results for young persons. The ANOVA for young participants revealed a significant main effect of group, $F(1, 24) = 12.77$, $MSE = 4.97$, $p < .005$, indicating that young trained ($M = 6.10$) recalled significantly more four-letter sequences compared with young controls ($M = 3.86$). A significant main effect of session was also found, $F(1, 24) = 111.32$, $MSE = 1.73$, $p < .001$, showing that the number of recalled four-letter sequences differed significantly between pretest ($M = 3.03$) and Posttest 1 ($M = 6.93$). More importantly, the Group × Session interaction was significant, $F(1, 24) = 34.51$, $MSE = 1.73$, $p < .001$, indicating that the magnitude of gains was more pronounced for the trained young persons (see Figure 1).

Training results for older persons. The ANOVA revealed a significant main effect of group, $F(1, 25) = 12.18$, $MSE = 4.28$, $p < .005$, showing that old trained ($M = 3.00$) recalled significantly more four-letter sequences than old controls ($M = 1.00$). A significant main effect of session, $F(1, 25) = 41.71$, $MSE = 1.71$, $p < .001$, showed that performance was higher at Posttest 1 ($M = 3.17$) compared with pretest ($M = 0.83$). As with the young adult group, the Group × Session interaction was significant for the older participants, $F(1, 25) = 25.80$, $MSE = 1.71$, $p < .001$, confirming that the old trained gained more from pretest to Posttest 1 compared with the old controls (see Figure 1).

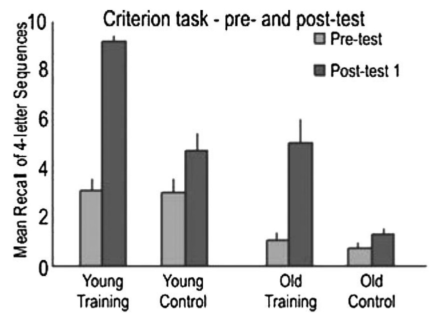

Figure 1. Mean number of correctly recalled four-letter sequences at pretest and Posttest 1 by young and older adults. Error bars are standard errors around the means.

Age differences in training results. To investigate whether the magnitude of training-related gains following updating training differed between young and older adults, a 2 (Group: young trained, old trained) × 2 (Session: pretest, Posttest 1) mixed ANOVA was performed on the letter memory task. The ANOVA revealed a significant main effect of group, $F(1, 24) = 23.38$, $MSE = 5.22$, $p < .001$, indicating that young trained ($M = 6.10$) recalled significantly more four-letter sequences compared with old trained ($M = 3.00$). A significant main effect of session was also found, $F(1, 24) = 162.29$, $MSE = 2.05$, $p < .001$, showing that the number of recalled four-letter sequences differed significantly between pretest ($M = 1.99$) and Posttest 1 ($M = 7.11$). More importantly, the Group × Session interaction was significant, $F(1, 24) = 5.49$, $MSE = 11.27$, $p < .05$, indicating that the improvement was more pronounced for the young trained than the old trained.

These results indicate a selective improvement on the criterion task immediately after training for both young and older trained persons relative to controls (cf. Dahlin et al., 2008). Indeed, all trained participants showed substantial improvement in letter memory performance from the first to the last training session (see Figure 2). In addition, it was found that young trained improved more compared with old trained.

Age-Related Differences During Training (Training Tasks)

To assess age-related differences in gains across the 5 weeks of training, mean values from the training tasks for Week 1 and Week 5 were compared between age groups. The reason for including only the first and last training week in these analyses is that all participants were at the same difficulty level (low at Week 1, high at Week 5) at these weeks, whereas the difficulty levels differed between participants during Weeks 2–4. All tasks were analyzed

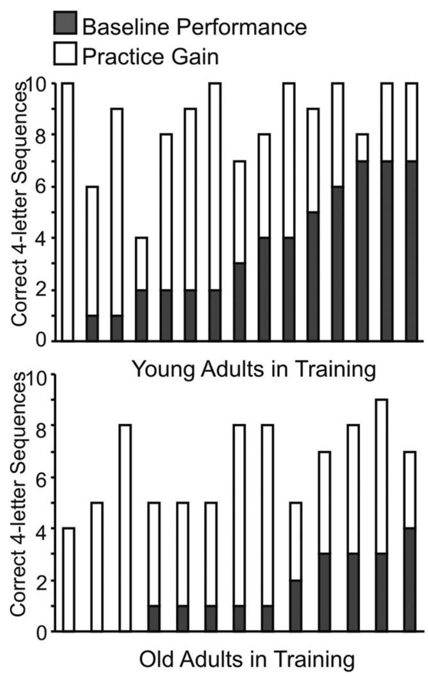

Figure 2. Individual practice gains for young and older trained participants. All trained participants improved in recall of four-letter sequences from the first to the last training session.

by separate 2 (Group: young trained, old trained) × 2 (Week: 1, 5) mixed ANOVAs.

The ANOVAs for letter memory, color memory, number memory, and spatial memory yielded virtually identical patterns of results. In the interest of space, these findings are therefore presented in condensed form. For all four tasks, there were significant main effects of age group (young > old), with F values ranging between 13.90 and 40.57 (all ps < .001). There were also main effects of week (5 > 1), with F values ranging from 13.03 to 52.09 (all ps < .001). By contrast, all Age Group × Week interactions fell short of significance (all ps > .50). As shown in Figure 3A, the magnitude of improvement across the training period was strikingly similar for young and older persons in these tasks.

For the remaining training task, keep-track, we found ceiling effects (M > 80% correct answers) during the first training week in the version with adjusted difficulty level (young M = 8.3, older M = 7.3, maximum = 9.0). Therefore, the keep-track version with five boxes was used to investigate potential training effects. The ANOVA revealed a significant main effect of group, $F(1, 26) = 19.70$, $MSE = 2.91$, $p < .001$, indicating that young trained (M = 10.98) categorized more words correctly than old trained (M = 8.95). A significant main effect of session, $F(1, 26) = 10.68$, $MSE = 1.12$, $p < .005$, was also found, indicating that participants improved their performance from Week 1 (M = 9.50) to Week 5 (M = 10.43). Finally, a reliable Group × Session interaction, $F(1, 26) = 6.47$, $MSE = 1.12$, $p < .05$, showed that the young participants, but not the older participants, improved keep-track performance across the 5 weeks (see Figure 3B).

Transfer Tasks

To assess the generalizability of updating training to untrained tasks, all transfer tasks were analyzed separately with 2 (Group: training, control) × 2 (Session: pretest, Posttest 1) mixed ANOVAs for each age group separately. In the following, we highlight only the results from the Group × Session interaction and, given a significant interaction effect, further investigate whether the transfer effect differed between young and older trained participants. Means, standard deviations, and p values are shown in Table 2.

Mental speed. There were no significant interactions involving group and session (ps > .05). Thus, no transfer was seen from updating training to digit dymbol performance.

Working memory. Four working memory transfer tasks were used: digit span forward, digit span backward, computation span, and 3-back. Owing to technical problems, we lost computation span data from 1 participant in the young control group and 3-back data from 2 participants in the old training group.

For the digit and computation span tasks, there were again no significant interactions (ps > .05), indicating lack of transfer to these three working memory tasks in both age groups.

A significant Group × Session interaction, $F(1, 24) = 5.93$, $MSE = 2.47$, $p < .05$, emerged for the young adults in the 3-back task, which indicated that the young trained improved more from pretest to Posttest 1 compared with the young controls (cf. Dahlin et al., 2008).

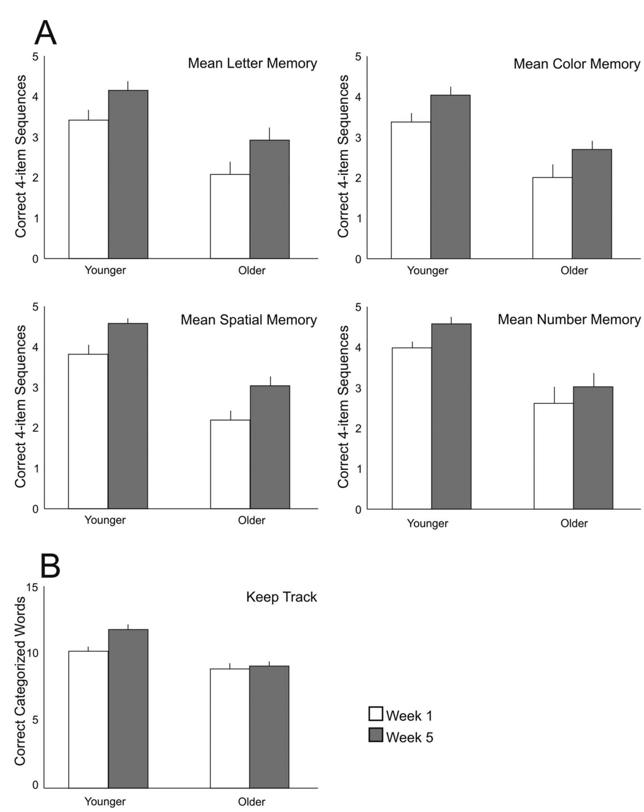

Figure 3. Mean performance in five updating tasks in young and older adults during the training period (first week vs. last week). Error bars are standard errors around the means.

Table 2
Performance in Transfer Tasks on Young and Old Adults as a Function of Training

Transfer task	Young trained Pretest (n = 15)	Young trained Posttest 1 (n = 15)	Young trained Posttest 2 (n = 11)	Young control Pretest (n = 11)	Young control Posttest 1 (n = 11)	Young control Posttest 2 (n = 7)	Transfer effect (p)	Old trained Pretest (n = 13)	Old trained Posttest 1 (n = 13)	Old trained Posttest 2 (n = 13)	Old control Pretest (n = 16)	Old control Posttest 1 (n = 16)	Old control Posttest 2 (n = 7)	Transfer effect (p)
Digit symbol	60.40 (9.40)	64.07 (8.96)	66.09 (8.93)	65.82 (9.45)	69.91 (11.40)	67.86 (11.82)	.833	46.38 (8.55)	50.15 (9.34)	47.23 (9.57)	46.63 (7.83)	47.38 (8.13)	45.29 (6.13)	.070
Digit span (forward)	7.67 (2.02)	8.07 (2.22)	9.09 (1.97)	8.73 (2.01)	8.64 (2.66)	9.14 (1.46)	.506	7.00 (2.24)	7.77 (1.88)	7.23 (1.30)	7.44 (2.13)	8.38 (2.47)	8.43 (1.72)	.781
Digit span (backward)	8.33 (2.16)	8.33 (1.80)	8.73 (2.01)	9.00 (3.03)	9.36 (2.66)	9.43 (1.72)	.649	6.23 (2.13)	7.38 (1.85)	7.62 (1.66)	7.94 (2.67)	7.63 (2.58)	8.71 (1.38)	.079
3-back	26.53 (3.44)	32.13 (2.88)	32.18 (3.76)	26.55 (4.72)	30.00 (4.43)	29.71 (5.06)	.023	19.36 (9.15)	21.82 (8.00)	24.91 (5.89)	17.75 (8.71)	22.00 (5.93)	24.71 (4.57)	.517
Computation span	3.13 (1.19)	3.40 (1.35)	4.27 (1.62)	3.40 (1.27)	4.20 (1.55)	4.29 (1.25)	.413	2.38 (0.77)	2.62 (0.65)	2.62 (1.04)	2.50 (1.16)	2.63 (2.83)	2.57 (1.51)	.877
Recall of concrete nouns	39.60 (5.46)	45.60 (5.30)	43.36 (5.75)	40.73 (6.17)	40.36 (7.50)	44.57 (2.88)	.005	33.38 (6.50)	35.77 (7.68)	34.00 (7.64)	32.38 (7.38)	34.63 (7.67)	33.86 (2.91)	.935
Paired associations	15.60 (2.06)	15.00 (3.38)	14.82 (3.43)	15.73 (2.05)	15.27 (2.90)	16.14 (1.07)	.908	11.00 (3.93)	11.85 (3.21)	11.46 (3.38)	12.50 (3.95)	12.94 (3.44)	13.14 (2.97)	.751
Letter fluency	51.93 (11.99)	55.93 (10.07)	57.72 (10.96)	56.09 (12.32)	60.82 (13.04)	58.71 (14.14)	.792	44.62 (14.37)	47.92 (14.68)	43.92 (14.13)	45.94 (7.67)	44.88 (8.94)	46.43 (6.19)	.068
Category fluency	34.20 (8.13)	37.60 (7.79)	41.64 (12.60)	36.63 (7.41)	40.72 (6.57)	40.29 (8.67)	.715	33.23 (4.09)	36.77 (6.02)	35.00 (4.85)	31.00 (5.27)	33.94 (6.27)	33.14 (5.96)	.758
Raven's Advanced Progressive Matrices	11.47 (2.39)	12.80 (2.57)	12.09 (2.39)	12.00 (2.72)	12.55 (1.97)	13.00 (2.24)	.535	5.31 (2.25)	6.38 (2.84)	6.54 (1.98)	5.56 (2.25)	6.50 (2.48)	6.14 (2.41)	.875

Note. Values indicate means (and standard deviations). $n = 10$ for young control in computation span pretest and Posttest 1; $n = 11$ for old trained in 3-back pretest, Posttest 1, and Posttest 2. The p values from the interaction (Pretest, Posttest 1 × Trained, Control) are reported under transfer effect.

For the older participants, there was no significant Group × Session interaction ($p = .52$). Thus, no transfer effects were seen for the older adults in the 3-back task. To compare age differences in transfer effects for the 3-back task, we performed a 2 (Group: young trained, old trained) × 2 (Session: pretest, Posttest 1) ANOVA, which revealed a significant Group × Session interaction, $F(1, 24) = 5.66$, $MSE = 5.55$, $p < .05$, showing that young trained improved more from pretest to Posttest 1 compared with old trained (see Table 2).

Episodic memory. For paired-associate learning, there were no reliable interactions involving session and group (ps $> .05$), indicating nonexistent transfer.

For recall of concrete nouns, a significant Group × Session interaction was obtained for the young groups, $F(1, 24) = 9.48$, $MSE = 13.55$, $p < .005$, which indicated a more pronounced improvement between pretest to Posttest 1 for the young trained compared with young controls. For the older groups, the Group × Session interaction was not significant ($p = .94$). To compare age differences in transfer effects for recall of concrete nouns, we performed a 2 (Group: young trained, old trained) × 2 (Session: pretest, Posttest 1) ANOVA, which revealed a significant Group × Session interaction, $F(1, 26) = 4.61$, $MSE = 9.87$, $p < .05$, showing that young trained improved more from pretest to Posttest 1 compared with old trained.

Verbal fluency and reasoning. For the two fluency tasks and reasoning, all interactions involving group and session were nonsignificant (ps $> .05$).

Taken together, the main outcome of the analyses of transfer was limited generalizability of updating training to other cognitive domains. Notably, however, in the young group a predicted transfer effect was observed for 3-back, which, similar to the training program, taxes updating in working memory.

Long-Term Maintenance

To investigate whether the immediate training gains were maintained 18 months after completion of training, a 2 (Group: trained, control) × 3 (Session: pretest, Posttest 1, Posttest 2) mixed ANOVA was performed separately for each age group. Participants who took part in the 18-month follow-up were included in the analyses, and a significant difference between pretest and Posttest 2 performance was interpreted as a maintenance effect. Means and standard errors are provided in Figure 4.

Maintenance for young. For the young participants, a significant main effect of group was found, $F(1, 16) = 14.03$, $MSE = 5.93$, $p < .005$, indicating that young trained ($M = 6.55$) recalled significantly more four-letter sequences compared with young controls ($M = 4.00$). A significant main effect of session was also found, $F(2, 32) = 37.54$, $MSE = 1.57$, $p < .001$, indicating that performance differed significantly between pretest ($M = 3.23$), Posttest 1 ($M = 6.86$), and Posttest 2 ($M = 5.73$). Also, the Group × Session interaction was significant, $F(2, 32) = 10.22$, $MSE = 1.57$, $p < .001$. Follow-up paired t tests revealed that young trained showed a reliable decrease in performance between Posttest 1 and Posttest 2, $t(10) = 3.19$, $p < .01$, although their Posttest 2 performance was significantly higher compared with pretest, $t(10) = 6.33$, $p < .001$. By contrast, Posttest 1 performance for the control group did not differ from Posttest 2 performance ($p = .48$), and Posttest 2 performance did not differ reliably

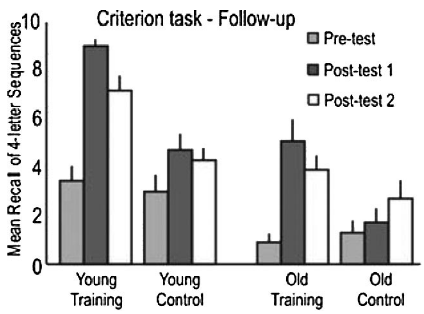

Figure 4. Mean number of correctly recalled four-letter sequences at pretest, Posttest 1, and Posttest 2 by young and older adults. Error bars are standard errors around the means. The bars are based only on individuals included in Posttest 2; therefore, pretest and Posttest 2 values differ slightly from those in Figure 1.

from that at pretest ($p = .09$). Hence, 18 months after training, the young trained performed at a higher level than at pretest, whereas the young controls performed at a similar level as at pretest.

Maintenance for old. The 2 (Group: trained, control) × 3 (Session: pretest, Posttest 1, Posttest 2) ANOVA for the older participants revealed a main effect of session, $F(2, 32) = 13.54$, $MSE = 2.15$, $p < .001$, indicating that number of correct four-letter sequences differed significantly between pretest ($M = 1.10$), Posttest 1 ($M = 3.40$) and Posttest 2 ($M = 3.31$). The Group × Session interaction was significant, $F(2, 32) = 7.06$, $MSE = 2.15$, $p < .005$, reflecting that the old trained group maintained Posttest 1 performance level at Posttest 2 ($p = .11$), where performance was reliably higher than at pretest, $t(10) = 5.56$, $p < .001$. Moreover, the old controls did not show any reliable change across test occasions ($ps > .08$). Hence, the old trained adults performed at reliably higher levels 18 months after completion of training than at pretest, whereas the old controls did not.

Maintenance of transfer effects. To investigate potential long-term transfer effects in the young adults, we performed a 2 (Group: trained, control) × 3 (Session: pretest, Posttest 1, Posttest 2) ANOVA on the 3-back data. We obtained a significant Group × Session interaction, $F(2, 32) = 3.19$, $MSE = 10.69$, $p = .05$. The key point here is that trained persons and controls maintained their performance levels at Posttest 2 (see Table 2), $F(1, 16) = 0.02$, $MSE = 3.69$, $p > .05$. Follow-up paired *t* tests revealed that young trained maintained Posttest 1 performance level at Posttest 2 ($p = .57$), although their Posttest 2 performance differed significantly compared with pretest, $t(10) = 0.59$, $p < .001$. By contrast, Posttest 1 performance for the control group did not differ from Posttest 2 performance ($p = .81$), and Posttest 2 performance did not differ reliably from that at pretest ($p = .05$). Hence, 18 months after training, the young trained performed at a higher level than at pretest, whereas the young controls performed at a similar level as at pretest (see Table 2).

The long-term follow-up ANOVA for concrete nouns also revealed a significant Group × Session interaction, $F(2, 32) = 5.92$, $MSE = 10.85$, $p < .01$. Follow-up paired *t* test revealed that young controls did not differ in performance from Posttest 1 to Posttest 2 ($p = .08$), and Posttest 2 performance did not differ reliably from that at pretest ($p = .08$). The young trained showed a decrease from Posttest 1 to Posttest 2, $t(10) = 4.72$, $p < .05$; however, their Posttest 2 performance did not differ from that at pretest ($p = .08$). Hence, the immediate transfer effect for the young trained was not maintained over time in this task (see Table 2).

Discussion

The main purpose of the present study was to investigate performance changes after 5 weeks of updating training and to determine whether improved performance would transfer to untrained tasks in young and older adults. Also, potential 18-month maintenance of training effects on the criterion and transfer tasks were examined. We found that after participating in a 5-week computerized adaptive training program, both young and older persons improved their performance substantially on the letter memory criterion task, suggesting that the ability to update working memory is modifiable from early through late adulthood. The analyses of age-related changes in the magnitude of absolute levels of gain showed an advantage for young adults (cf. Baltes & Kliegl, 1992; Dahlin et al., 2008; Jones et al., 2006; Kray & Epplinger, 2006). For the present purposes, however, the key finding is that the older adults did show substantial training-related gains, gains that in relative terms were comparable to or even greater than those of the young adults. To further underscore the consistency of the training-related gain in young as well as older adults, it should be stressed that the effect was not driven by a subset of the sample, but all participants showed clear improvements in letter memory performance. The impression of a robust training-related improvement by the older adults was further underscored by the results from the training tasks, where both young and older adults increased their performance on the four training tasks that required updating of single items (i.e., letters, numbers, colors, and spatial locations; cf. Figure 3A). The only exception was the keep-track task, in which young but not older adults showed training-related gains (cf. Figure 3B). Most critically, however, after training, the older participants performed above the initial baseline performance level for young adults on the criterion task (letter memory; cf. Figure 1).

As for maintenance of training gains, we demonstrated 18-month maintenance effects of enhanced letter memory performance for both young and older adults. These results extend previous findings (Erickson et al., 2007; Kramer et al., 1999; Stigsdotter Neely & Bäckman, 1993; Willis et al., 2006) by demonstrating long-term maintenance of gains following updating training during a comparatively long period. Perhaps even more remarkable is the fact that the older participants performed above the initial baseline level of the young participants on the criterion task at Posttest 2. Hence, these findings demonstrate that executive plasticity appears to be a robust rather than a transient phenomenon in both young and older adults.

In the current study, we included an extensive battery of transfer tests covering four broad cognitive domains: mental speed, working memory, episodic memory, and reasoning. Two results are particularly noteworthy. First, as we reported previously (Dahlin et al., 2008), the young trained adults improved significantly on the nontrained 3-back task relative to the young control group. Second, a novel finding is that this transfer effect was maintained 18 months after training. As both the letter memory criterion task and the 3-back transfer task engage common updating processes, these data suggest that the improvement seen in the young trained adults reflects a change at the skill level rather than task-specific stimulus–response facilitation. As alluded to in the introduction, this finding is consistent with the view that a key prerequisite for the occurrence of transfer is that the transfer task taps similar cognitive operations as the training task (Thorndike & Woodworth, 1901), a point that was also discussed in a recent study (Jaeggi et al., 2008). Although letter memory and *n*-back share cognitive operations, it is important to note that they differ on several dimensions, including memorial content, set size, presentation rate, and patterns of functional brain activation (Dahlin et al., 2008). Perhaps most critically, the letter memory task involves continuous updating with responses after each list presentation, whereas the *n*-back task requires a response upon the presentation of every new item. These differences are critical, given that previous research has indicated that even quite subtle procedural variations can affect the degree of transfer (Derwinger et al., 2003; Verhaeghen & Marcoen, 1996).

An improvement for young trained adults was also seen in one of the episodic memory tasks, recall of concrete nouns, immediately after training. This task was administered according to a selective reminding procedure (see Method section), in which the participants, to be successful in recalling all items, have to keep track of items that were recently presented as well as items that were recalled on the last trial. This particular feature to keep track of reminded and nonreminded items may require updating of memory representations, and we probably found transfer effects to this specific episodic memory task, because of operational overlap with the trained tasks. However, the inconsistency of the transfer effect (the young trained improved from pretest to Posttest 1 and declined to Posttest 2, whereas the young controls improved from Posttest 1 to Posttest 2) suggests caution in interpreting these data. The older trained participants did not show improvement in any of the transfer tasks relative to the old control group. This is in line with most previous studies showing small or nonexistent transfer effects in older adults (Ball et al., 2002; Derwinger et al., 2003; Stigsdotter Neely, & Bäckman, 1993).

In light of marked training gains in the criterion task for both young and older adults, a key issue is why the young, but not the old, showed transfer to 3-back. One possibility is that the superior level of updating performance reached by the young trained adults is important in driving the selective transfer effect. A higher level of performance likely reflects greater efficiency in updating skill, and the fact that the older adults, despite large improvement, never reached that level of proficiency may be a chief reason underlying their lack of transfer. Thus, not only the magnitude of improvement but also the performance level reached may be important for transfer to occur. The lack of transfer effects in older adults also suggests that older adults may have more limited neural plasticity compared with young adults. As demonstrated by Dahlin et al. (2008), age-related alterations in striatal function may contribute to the limited transfer effects shown by older adults.

In closing, the present study showed substantial plasticity of executive functioning (improvement in letter memory from updating training) in both young and older adults that was maintained 18 months later, although transfer effects limited to another task requiring updating was seen in young persons only.

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