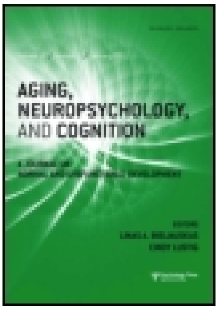


Aging, Neuropsychology, and Cognition: A Journal on Normal and Dysfunctional Development
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/nanc20

Working memory training improvements and gains in non-trained cognitive tasks in young and older adults

Stephan Heinzel [a c] , Stefanie Schulte [a] , Johanna Onken [a] , Quynh-Lam Duong [a] , Thomas G. Riemer [a] , Andreas Heinz [b] , Norbert Kathmann [c] & Michael A. Rapp [a]

[a] Geriatric Psychiatry Center, Psychiatric University Hospital St. Hedwig , Berlin , Germany

[b] Department of Psychiatry and Psychotherapy , Campus Charité Mitte , Berlin , Germany

[c] Department of Psychology , Humboldt University , Berlin , Germany

Published online: 02 May 2013.

Aging, Neuropsychology, and Cognition, 2013
http://dx.doi.org/10.1080/13825585.2013.790338

Routledge
Taylor & Francis Group

Working memory training improvements and gains in non-trained cognitive tasks in young and older adults

Stephan Heinzel[1,3], Stefanie Schulte[1], Johanna Onken[1], Quynh-Lam Duong[1], Thomas G. Riemer[1], Andreas Heinz[2], Norbert Kathmann[3], and Michael A. Rapp[1]

[1]Geriatric Psychiatry Center, Psychiatric University Hospital St. Hedwig, Berlin, Germany
[2]Department of Psychiatry and Psychotherapy, Campus Charité Mitte, Berlin, Germany
[3]Department of Psychology, Humboldt University, Berlin, Germany

ABSTRACT

Previous studies on working memory training have indicated that transfer to non-trained tasks of other cognitive domains may be possible. The aim of this study is to compare working memory training and transfer effects between younger and older adults ($n = 60$). A novel approach to adaptive n-back training (12 sessions) was implemented by varying the working memory load and the presentation speed. All participants completed a neuropsychological battery of tests before and after the training. On average, younger training participants achieved difficulty level 12 after training, while older training participants only reached difficulty level 5. In younger participants, transfer to Verbal Fluency and Digit Symbol Substitution test was found. In older participants, we observed a transfer to Digit Span Forward, CERAD Delayed Recall, and Digit Symbol Substitution test. Results suggest that working memory training may be a beneficial intervention for maintaining and improving cognitive functioning in old age.

Keywords: Aging; Working memory; Training; Transfer; Processing speed; Executive functions.

This work was supported in part by the German National Academic Foundation grant to S.H.; the German Ministry for Education and Research (BMBF 01QG87164 and 01GS08195 and 01GQ0914) and by a MaxNetAging award to M.A.R. We thank Amit Evron for proofreading the manuscript. Fractions of the current work are part of two unpublished dissertation theses. No conflicts of interest are to report.

Address correspondence to: Stephan Heinzel, Dipl.-Psych., Geriatric Psychiatry Center, Psychiatric University Hospital St. Hedwig, Charité Berlin, Grosse Hamburger Str. 5-11, 10115 Berlin, Germany. E-mail: stephan.heinzel@charite.de

Performing complex tasks in everyday life requires the use of working memory, a limited capacity system allowing the temporary storage and manipulation of information (Baddeley, 2000; Baddeley & Hitch, 1974). Previous research has indicated that this cognitive system is especially prone to decline associated with aging (for review see Braver & West, 2008; Park & Payer, 2006). In recent decades, considerable efforts have been made to investigate and understand the mechanisms of age-related decline in working memory, including behavioral and neuroimaging approaches. From a neuroscientific perspective, it seems that age-related changes in brain structure and function affect task performance in various cognitive domains including working memory (for reviews see Buckner, 2004; Grady, 2012; Greenwood, 2007; Rajah & D'Esposito, 2005; Reuter-Lorenz & Park, 2010). Despite these age-related changes, training studies have suggested that older adults are able to improve their working memory performance through training (Borella, Carretti, Riboldi, & De Beni, 2010; Brehmer, Westerberg, & Baeckman, 2012; Buschkuehl et al., 2008; Carretti, Borella, Zavagnin, & de Beni, 2012; Dahlin, Neely, Larsson, Baeckman, & Nyberg, 2008; Dahlin, Nyberg, Baeckman, & Neely, 2008; Li et al., 2008; Penner et al., 2012; Richmond, Morrison, Chein, & Olson, 2011; von Bastian, Langer, Jaencke, & Oberauer, 2012; Zinke, Zeintl, Eschen, Herzog, & Kliegel, 2012). A key question – regarding cognitive training research – is, whether improvements in a trained task can transfer to other non-trained tasks. Two important goals are: (1) to identify training procedures that are successful in improving not only task-specific skills, but general cognitive abilities and (2) to gain a more precise understanding of underlying mechanisms that are responsible for transfer effects.

Theoretical considerations of cognitive transfer go back to Thorndike (1906) who stated that transfer can be expected if tasks involve common process components ("elements"). Therefore, transfer within the same cognitive domain (e.g., working memory) appears to be more likely than transfer to other cognitive domains. In a recent discussion on the taxonomy of transfer effects (Noack, Loevdén, Schmiedek, & Lindenberger, 2009), the former would be considered "near transfer", and the latter, "far transfer". This classification refers to the structure of abilities proposed by Carroll (1993).

Recent reviews on cognitive training and transfer studies (Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Noack et al., 2009; Zelinski, 2009) have shown several reports on near transfer effects, whereas far transfer appears to be very limited, especially in older adults (e.g., Ball et al., 2002; Owen et al., 2010). This observation also seems to hold for the domain of working memory training (for recent reviews see Klingberg, 2010; Melby-Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012). In studies that have investigated older participants, only few have reported far transfer effects (Borella et al., 2010; Brehmer et al., 2012; Buschkuehl et al., 2008; Penner et al., 2012; Richmond et al., 2011). Borella et al. (2010) trained a group of older participants in a verbal working memory task (categorization working memory span task) and found transfer to the Cattell test, Stroop Color interference, and a pattern comparison test. The authors concluded that their training procedure led to improvements in fluid intelligence, inhibition-related processes, and processing speed. Buschkuehl et al. (2008) showed transfer to a visual free recall task (episodic memory) after training in three spatial working memory tasks. Richmond et al. (2011) conducted a training program with a verbal and a spatial complex working memory span task and found transfer to the number of repetitions in the California Verbal Learning Test (episodic memory). Penner et al. (2012) tested the effects of a computerized working memory training program with three different modules. Far transfer was only reported for a processing speed task. The authors interpret this finding in terms of an increased ability to control attention. In the study by Brehmer et al. (2012), younger and older participants completed a training procedure including seven verbal and non-verbal working memory tasks. Compared to low level practice, adaptive working memory training resulted in larger training and transfer effects in the paced auditory serial addition task (sustained attention) and the cognitive failure questionnaire (self-rating scale for cognitive functioning in daily life).

Reviewing the inconsistent findings from the working memory training and transfer literature in aging, the question remains: under which circumstances may far transfer effects be possible? Generally speaking, it has been stated that far transfer may be more likely if "general, deep principles" (cf. Barnett & Ceci, 2002, p. 625) are being trained. More specifically, Hertzog, Kramer, Wilson, and Lindenberger (2008) argued that far transfer may require cognitive training procedures involving executive control, the use of attention, processing speed, or conscious cognitive control.

It seems that adaptive working memory training may meet several of these requirements and may enable participants to achieve their potential for improvement (Baltes, Sowarka, & Kliegl, 1989; Doumas, Rapp, & Krampe, 2009). In previous studies, task difficulty was adapted to individual task performance by changing the working memory load. This type of training procedure seems to disregard one important aspect of task performance: the time required to process and respond to target stimuli. Processing speed was found to be a major factor contributing to individual differences in various cognitive abilities (e.g., Verhaeghen & Salthouse, 1997). In aging research, an age-related reduction in processing speed has been related to performance decline in working memory and other cognitive functions (Salthouse, 1996). In his processing speed theory of adult age, Salthouse (1996) described processing speed as being a sort of mental "bottle neck" for successfully performing many cognitive tasks. Therefore, if a training procedure targets processing speed performance, improvements in other cognitive tasks seem to be plausible.

Training studies that include training of speeded responses by increasing the presentation speed of stimuli (e.g., Peng, Wen, Wang, & Gao, 2012; Takeuchi et al., 2011) have indicated that processing speed performance can be increased if explicitly addressed in the training regime (see also Acevedo & Loewenstein, 2007; Ball et al., 2002; Guenther, Schaefer, Holzner, & Kemmler, 2003). From this perspective, a training procedure that is adaptive in terms of working memory load and presentation speed appears to be a promising approach. In the present study, the *n*-back paradigm was chosen for working memory training because it reliably taps the executive component of working memory (i.e., the continuous updating of stimuli and attentional control), and speeded responding (Conway, Kane, & Engle, 2003).

The purpose of the current study is to investigate to what extent working memory can be trained by adaptive training in older adults, and how training gains compare between younger and older adults. A stable training-induced increase in working memory performance would be of general relevance since working memory is an essential component in various domains of everyday assignments (Ball et al., 2002). To our knowledge, this is the first working memory training study that adaptively manipulates working memory load as well as presentation speed in older adults.

Hypotheses on transfer effects to non-trained tasks

In order to assess whether working memory training influences task performance in other cognitive domains, we tested possible transfer effects to non-trained tasks of short-term memory, episodic memory, processing speed, executive functions, and fluid intelligence. In this study, we were not able to recruit enough participants to perform analyses on the level of latent variables; therefore, we chose specific tests as “proxies” for cognitive constructs. When analyzing data on the level of observed variables (i.e., the performance scores of the obtained tasks) as has been done in the majority of previous training research, the problem arises that no single task is “process pure”. Therefore, conclusions about the involvement of specific process components and about improvements of any general cognitive ability should be interpreted with caution.

Transfer to short-term memory

The task we chose as a proxy for short-term memory was the Digit Span task. This task has frequently been used in working memory training studies and has usually served as a “near-transfer task” because short-term memory and working memory are closely related (for review see Bopp & Verhaeghen, 2005). We expected training-related improvements in the ability to maintain information in working memory, therefore we hypothesized gains in the untrained Digit Span task, in both Digit Span forward (Digit Span Fwd) and backward (Digit Span Bwd).

Transfer to episodic memory

Recent working memory training studies have found transfer to episodic memory tasks (Buschkuehl et al., 2008; Richmond et al., 2011; Schmiedek, Loevdén, & Lindenberger, 2010). Several explanations for this transfer have been discussed: effective retrieval in episodic memory could be related to an increased working memory capacity (Bunting, Conway, & Heitz, 2004; Shelton, Elliott, Matthews, Hill, & Gouvier, 2010). Also, the ability to encode information may be enhanced through the working memory training procedure, possibly through an improvement in phonological loop capability (Burgess & Hitch, 2005). We used the immediate and delayed recall of wordlists from the neuropsychological test battery of the Consortium to Establish a Registry for Alzheimer's Disease (CERAD, Morris et al., 1989) as a measure of episodic memory. We hypothesized a transfer to the amount of words recalled immediately (CERAD Imm Recall) and after a delay of 15 minutes (CERAD Del Recall).

Transfer to processing speed

By decreasing the interstimulus interval, we intended to train the ability to respond as fast as possible to target stimuli. In memory research, an increase in presentation speed by reducing the interstimulus interval has been frequently associated with an increase in task difficulty (e.g., Intraub, 1980; Proctor, 1983; Wright et al., 1990). At the same time, training studies indicate that processing speed performance is trainable (Peng et al., 2012; Takeuchi et al., 2011). Therefore, we expected a transfer to a processing speed task. We chose the Digit Symbol Substitution task (Digit Symbol) as a measure for processing speed since it has been frequently used in other studies (for review see Salthouse, 1996).

Transfer to executive functions

Through the adaptive increase of working memory load, we expected participants to better cope with an increasing executive demand (the updating of information). At the same time, participants have to constantly inhibit responding to previous target stimuli. A relationship between the executive component of working memory (Baddeley & Hitch, 1974) and executive functions has been shown (D'Esposito et al., 1995; Engle, Tuholski, Laughlin, & Conway, 1999; Gray, Chabris, & Braver, 2003). As a proxy for executive functions, we chose a speeded Verbal Fluency task (Verbal Fluency) because we anticipated transfer to the rule-guided production of words in this task.

Transfer to fluid intelligence

Working memory and fluid intelligence have been found to share a relatively high percentage of variance (Ackerman, Beier, & Boyle, 2005; Conway et al., 2003; Kyllonen & Christal, 1990). It has been proposed that the relationship between working memory and fluid intelligence may be partly moderated by processing speed (Burgaleta & Colom, 2008; Clay et al., 2009; Zimprich & Martin, 2002) and executive control (Chen & Li, 2007, Conway et al., 2003). Since processing speed and executive functions were expected to improve through our training approach, we expected to find a transfer effect to fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008) in the current study. We used Raven's Standard Progressive Matrices (Raven's SPM) and the Figural Relations subtest of a German intelligence test (Leistungspruefsystem, LPS, Horn, 1983). Raven's SPM has found wide application in intelligence research (Carpenter, Just, & Shell, 1990). We included the LPS as another nonverbal test of intelligence to increase the validity of possible transfer effects.

Previous studies, comparing training and transfer effects between younger and older adults have reported younger adults to perform better on training and transfer tasks both at baseline and after training (Brehmer et al., 2012; Dahlin, Neely, et al., 2008; Dahlin, Nyberg, et al., 2008; Li et al., 2008; Schmiedek et al., 2010). Furthermore, the magnitude of training-induced improvements in trained and non-trained tasks has been found to be larger in younger adults. These findings have been associated with age-related changes in brain structure and functioning (e.g., Grady, 2012; Greenwood, 2007; Rajah & D'Esposito, 2005; Reuter-Lorenz & Park, 2010), leading to reduced performance of cognitive systems in older participants when challenged at their "limit of performance" (Willis, 1990) as done in adaptive training programs. Younger adults, however, seem to be able to better adapt to increasing task demands, presumably due to larger neural resources (Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2009). Therefore, we expected younger adults to outperform older adults in training gains and transfer effects in the current study.

METHOD

Participants

The sample consisted of 62 healthy participants that were randomly assigned to either training or control groups. Two older training participants were excluded from the sample because they missed more than two consecutive training sessions, resulting in an analysis sample of 60 participants in total. Fifteen younger participants (6 men, 9 women, $M = 25.9$, $SD = 1.9$, range: 24–30 years) and 15 older participants (5 men, 10 women,

$M = 66.07$, $SD = 4.7$, range: 61–75 years) took part in a 4-week *n*-back working memory training program. A group of 15 younger participants (6 men, 9 women, $M = 25.6$, $SD = 2.1$, range: 22–30 years) and a group of 15 older participants (4 men, 11 women, $M = 65.6$, $SD = 3.9$, range: 60–72) did not participate in the training program and served as the control groups. Participants were recruited via newspaper advertisements, e-mail, and blackboard notes at Humboldt-University, Berlin and at sports clubs for senior citizens. Participants who completed the study received €150 (training groups) or €50 (control groups). There were no significant differences in age, gender distribution, and education between the training and control groups within each age group. Participants were not included in the study if they reported to have suffered from any kind of psychiatric or neurological disease in the past, had experienced any kind of head trauma or injury, or if their score on the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975) was below 28. Demographic variables are shown in Table 1.

Procedure

Both training groups completed a 4-week adaptive *n*-back working memory training (3 sessions per week, 12 sessions in total, session duration 45 minutes). All participants completed a battery of seven neuropsychological tests before (t1) and after (t2) the training period.

Materials and tests

For neuropsychological screening and the examination of possible transfer effects from working memory training to other tasks, tests were selected for measuring short-term memory (Digit Span Fwd, Digit Span Bwd), episodic memory (CERAD Imm Recall, CERAD Del Recall), processing speed (Digit Symbol), executive functions (Verbal Fluency), and fluid intelligence (Raven's SPM, LPS). Parallel versions were used for all tests except for CERAD Imm Recall, CERAD Del Recall, and Verbal Fluency at t1 and t2. The test versions were counterbalanced across participants. The CERAD is a standardized test and no parallel version of the wordlist was available. In Verbal Fluency, searching for words starting with a different letter would not lead to comparable results because of different mental search spaces; therefore no parallel version was used for this task.

Short-term memory transfer task

To obtain an estimate of each participant's short-term memory capacity, Digit Span Forward (Digit Span Fwd) and Backward (Digit Span Bwd) from the Wechsler Adult Intelligence Scale (WAIS, Wechsler, 1987) was administered. Lists of digits were read aloud to participants at a rate of one digit per second and participants were instructed to repeat the digits in the order

TABLE 1. Mean values, standard deviations and range of demographic measures and Mini-Mental Status Examination (MMSE) scores

	N	Gender (male/female)[1]	Age (mean [*SD*]/range)[2]	Years of education (mean [*SD*]/range)[2]	MMSE (mean [*SD*]/range)[2]
Young training group	15	6/9	25.93 [±1.94] 24–30	18.20 [±1.53] 16–21	29.93 [±0.26] 29–30
Young control group	15	6/9	25.60 [±2.06] 22–30	17.57 [±1.26] 15–19	29.73 [±0.46] 29–30
Old training group	15	5/10	66.07 [±4.68] 61–75	16.14 [±2.64] 12–20	29.66 [±0.62] 28–30
Old control group	15	4 /11	65.60 [±3.94] 60–72	16.00 [±3.44] 12–24	29.33 [±0.72] 28–30

Note: [1] χ^2-tests indicated that there are no significant differences in gender distribution between groups.
[2] Two sample *t*-tests showed that there were no significant differences in age, total education time, and MMSE between young training and control group, and between older training and control group, respectively. *t*-Tests comparing the age groups, showed that younger participants had more years of education ($t(58) = 2.96$, $p = .004$, Cohen's $d = 0.78$) and higher scores in the MMSE ($t(58) = 2.34$, $p = .023$, Cohen's $d = 0.61$).

of presentation or backwards. For each length of the digit lists, two trials were presented. The score used in the following analyses was determined by the length of the longest digit list that was correctly repeated. If participants failed to repeat both trials of a certain list length, the assessment of this task was terminated.

Episodic memory transfer task

As a measure of episodic memory, all participants performed the memory task from the neuropsychological test battery of the Consortium to Establish a Registry for Alzheimer's Disease (CERAD, Morris et al., 1989). Participants were asked to remember 10 words that were presented to them sequentially three times in varying order, and recall the words immediately after completion of each list and after a delay. For further analyses, the number of correctly recalled items immediately (CERAD Imm Recall) and after a delay of 15 minutes was used (CERAD Del Recall).

Processing speed transfer task

The Digit Symbol Substitution subtest (Digit Symbol) of the WAIS (Wechsler, 1987) was included to assess mental processing speed. In Digit Symbol, participants were instructed to copy symbols as quickly as possible into empty boxes located below a random sequence of numbers ranging from 1 to 9 according to a specific coding key. The score used for analyses was the number of correct symbols completed within 60 seconds.

Executive transfer task

Verbal Fluency requires the ability to generate words while monitoring previously recalled words and following specific rules (Larsson, Michel, Baeckstroem, & Johanson, 2007). Verbal Fluency was assessed by a German version of the Controlled Oral Word Association Test (COWAT, Benton & Hamsher, 1989). Participants were asked to generate as many words as possible starting with the letter "S" within 60 seconds (not including proper names or names of places and cities).

Fluid intelligence transfer tasks

Fluid intelligence was measured by Raven's Standard Progressive Matrices (Raven's SPM; Raven, Summers, & Birchfield, 1990) and by the Figural Relations subtest of a German intelligence test (LPS, Horn, 1983). To solve these tasks, participants were required to identify patterns of nonverbal symbols: In Raven's SPM, they were instructed to find a matching item to complete a pattern, while in the LPS, they had to mark the non-matching item of a pattern of symbols. For example, a sequence of vertical lines was presented while the amount of vertical lines varied systematically: || | || | || | | |. One item (in this example, item number 7) did not fit this pattern and had to be marked by the participants. Both intelligence tasks were timed and the scores were derived from the number of correct items accomplished within 7.5 minutes (Raven's SPM) or 3 minutes (LPS), respectively.

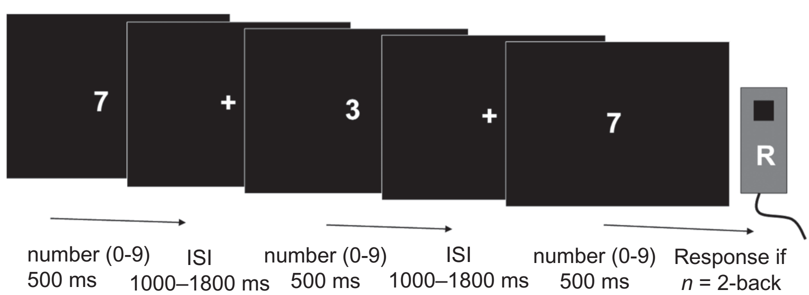
Screening for mild cognitive impairment

To rule out clinically relevant mild cognitive impairment (Petersen et al., 1999), we used the MMSE (Folstein et al., 1975), a short screening test addressing basic cognitive functions such as orientation, memory, reading and visuo-constructive abilities. Only participants with a total MMSE score of 28 or above were included in the study.

Adaptive *n*-back paradigm

We used a computerized version of the *n*-back paradigm (Cohen et al., 1993). In the *n*-back task, digits from 0 to 9 were visually presented in the center of an otherwise black screen in a randomized sequence one at a time. Stimulus duration was set to 500 ms, while the interval between stimuli (interstimulus interval) was varied across blocks between 1800 and 1000 ms. Each block consisted of 20 to 28 trials and 5 to 7 targets. There were six different *n*-levels: 0-, 1-, 2-, 3-, 4-, and 5-back. In the 0-back conditions, participants were asked to respond to the appearance of a specific digit ("0") by pressing a response button with their right index finger. In the 1-back condition, participants were asked to press the response button if the stimulus presented in the immediately preceding trial was identical to the current stimulus. In the 2-back condition, they were instructed to press the response button if the stimulus that was presented two trials before was the same as the current stimulus (see Figure 1). In 3-, 4-, and 5-back task the participants had to match numbers that were presented 3, 4, or 5 trials ago.

FIGURE 1. *n*-Back training paradigm (example: 2-back): white numbers were presented on a black background for 500 ms each, followed by a white fixation cross. The length of the interstimulus interval (ISI) varied from 1800 to 1000 ms according to the difficulty level.



Adaptive practice (Doumas et al., 2009) was used throughout all 12 training sessions in order to keep the task difficult. Each training session consisted of 3 runs, while each run consisted of 9 blocks. The difficulty level of the task varied across training runs according to individual performance. Task difficulty was increased by introducing higher working memory loads and by shortening the interstimulus interval from 1800 to 1000 ms. Unpublished data from a pilot study with 21 participants (11 younger, age 20–35, and 10 older, age 60–75) showed that difficulty levels of the *n*-back paradigm could be increased parametrically by increasing the working memory load ($R = -.41$, $p < .001$), and decreasing the interstimulus interval ($R = .25$, $p < .001$). Please contact the corresponding author for additional information on this pilot data.

All participants began training at session 1 with difficulty level 1 (0-, 1-, and 2-back, interstimulus interval = 1800 ms). If a subject successfully completed the first run (that is 3 blocks of 0-back, 3 blocks of 1-back, and 3 blocks of 2-back) with a hit rate of 80% or above within each block and with no false alarms, the next difficulty level was introduced in the following run. From level 1 to level 5, interstimulus interval gradually decreased from 1800 to 1000 ms in steps of 200 ms. At level 6, the next *n*-level was introduced (3-back), and 1-back was removed, i.e., participants completed 3 blocks of each 0-, 2-, and 3-back. In addition, interstimulus interval was set back to 1800 ms. This procedure continued until 5-back was introduced at level 16 (see Figure 2).

Statistics

Statistical analyses were performed using SPSS version 15.0 (SPSS, Chicago, IL, USA). The Kolmogorov–Smirnov test for deviation from a normal distribution indicated that all analyzed variables met assumptions for

FIGURE 2. Difficulty levels of the *n*-back training procedure: All participants started with difficulty level 1, which included 3 blocks of 0-, 1-, and 2-back each, at an interstimulus interval (ISI) of 1800 ms. If participants accomplished one level at a hit rate of >80% and did not make any false alarms, they moved to the next difficulty level.

Level	ISI	*n*-back	Level	ISI	*n*-back	Level	ISI	*n*-back
1	1800	0, 1, 2	**6**	1800	0, 2, 3	**11**	1800	0, 3, 4
2	1600	0, 1, 2	**7**	1600	0, 2, 3	**12**	1600	0, 3, 4
3	1400	0, 1, 2	**8**	1400	0, 2, 3	**13**	1400	0, 3, 4
4	1200	0, 1, 2	**9**	1200	0, 2, 3	**14**	1200	0, 3, 4
5	1000	0, 1, 2	**10**	1000	0, 2, 3	**15**	1000	0, 3, 4

parametric testing. Comparisons between groups and test time were then conducted using repeated measures general linear model analyses of variance (ANOVA). For follow-up analyses, *t*-tests were performed.

RESULTS

Differences between age groups in *n*-back performance at baseline (t1)

A *t*-test comparing the achieved difficulty level in *n*-back between the younger and older participants at baseline (t1) revealed no significant differences ($t(58) = 1.32$, $p = .194$, Cohen's $d = 0.35$).

Differences between age groups in neuropsychological measures at t1

To test for differences in neuropsychological measures between the two age groups at t1, *t*-tests (older vs. younger participants) were conducted for each test. The younger participants outperformed the older ones in CERAD Imm Recall ($t(58) = 5.85$, $p < .001$, Cohen's $d = 1.54$), CERAD Del Recall ($t(58) = 3.39$, $p = .001$, Cohen's $d = 0.89$), Digit Symbol ($t(58) = 8.56$, $p < .001$, Cohen's $d = 2.25$), Verbal Fluency ($t(58) = 2.25$, $p = .028$, Cohen's $d = 0.59$), Raven's SPM ($t(58) = 6.84$, $p < .001$, Cohen's $d = 1.80$), and LPS ($t(57) = 6.30$, $p < .001$, Cohen's $d = 1.67$). No differences between age groups were found at t1 in Digit Span Fwd ($t(58) = .31$, $p = .762$, Cohen's $d = 0.08$) and Digit Span Bwd ($t(58) = 1.30$, $p = .199$, Cohen's $d = 0.34$).

Differences between training and control groups within each age group at t1

t-Tests comparing training and control group in younger participants showed that the two groups did not differ from each other in *n*-back performance and all neuropsychological measures at t1 (all *p*s > .230).

Similarly, no differences between training and control group were found in *n*-back performance and all of the neuropsychological tests in the older participants at t1 (all *p*s > .076). Means and standard deviations of all test scores are shown in Table 2a (younger) and 2b (older participants).

Training gains in *n*-back

In younger adults, a significant group (training vs. control) by time (t1 vs. t2) interaction, $F(1, 28) = 148.84$, $MSE = 331.35$, $p < .001$, $\eta_p^2 = .842$, indicated that the young training participants achieved higher difficulty levels in the *n*-back task compared to the young control group (see Tables 2a and 3, and Figure 3). Older training participants were found to reach significantly higher difficulty levels at t2 compared to participants in the older control group, revealed by a group by time ANOVA, $F(1, 28) = 44.02$, $MSE = 45.07$, $p < .001$, $\eta_p^2 = .611$. Comparing the training achievements between

TABLE 2. Mean values and standard deviations of achieved difficulty levels in *n*-back and performance in neuropsychological measures that were administered before (t1) and after (t2) training/waiting period; *t*-values, *p*-values, and effect sizes (Cohen's *d*) for paired *t*-tests between t1 and t2 within each group (a) in younger participants and (b) in older participants

	Younger training ($n = 15$)[2]				Younger control ($n = 15$)			
Tasks[1]	t1 (mean [*SD*])	t2 (mean [*SD*])	Paired sample $t(14)$ [p]	Effect size (Cohen's *d*)	t1 (mean [*SD*])	t2 (mean [*SD*])	Paired sample $t(14)$ [p]	Effect size (Cohen's *d*)
(a) Younger participants								
n-Back (achieved level)	1.67 [±0.72]	11.93 [±3.20]	13.76 [< .001]	7.36	1.40 [±0.51]	2.27 [±0.96]	4.52 [< .001]	2.42
Digit Span Fwd	7.13 [±0.83]	7.67 [±0.49]	2.48 [.027]	1.33	7.47 [±0.64]	7.67 [±0.49]	1.38 [.189]	0.74
Digit Span Bwd	6.07 [±0.88]	6.67 [±0.82]	3.67 [.003]	1.96	5.80 [±1.21]	6.47 [±0.83]	2.65 [.019]	1.42
CERAD Imm Recall	28.73 [±2.05]	29.93 [±0.26]	2.36 [.033]	1.26	28.67 [±1.50]	29.47 [±0.74]	1.92 [.075]	1.03
CERAD Del Recall	9.47 [±0.83]	10.00 [±0.00]	2.48 [.027]	1.33	9.47 [±1.30]	9.80 [±0.77]	2.09 [.055]	1.12
Digit Symbol	45.40 [±7.11]	54.80 [±8.02]	5.96 [< .001]	3.19	43.13 [±4.32]	47.07 [±5.51]	3.70 [.002]	1.98
Verbal Fluency	19.93 [±3.79]	24.20 [±4.13]	2.96 [.010]	1.58	21.13 [±2.64]	21.13 [±4.79]	0.00 [1.00]	0.00
Raven's SPM	22.20 [±3.65]	24.53 [±2.90]	2.95 [.011]	1.58	22.73 [±2.84]	23.07 [±2.34]	.38 [.713]	0.20
LPS	24.93 [±2.73]	30.71 [±4.32]	5.23 [< .001]	2.90	24.87 [±3.04]	29.80 [±2.98]	6.15 [< .001]	3.29

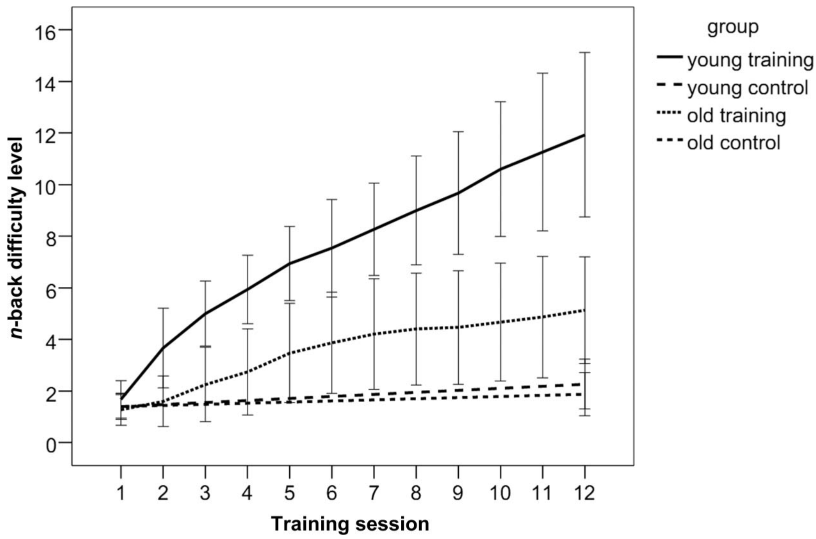
(Continued)

TABLE 2. (Continued)

	Older training ($n = 15$)				Older control ($n = 15$)			
	t1 (mean [*SD*])	t2 (mean [*SD*])	Paired sample $t(14)$ [p]	Effect size (Cohen's d)	t1 (mean [*SD*])	t2 (mean [*SD*])	Paired sample $t(14)$ [p]	Effect size (Cohen's d)
(b) Older participants								
n-Back (achieved level)	1.27 [±0.59]	5.13 [±2.07]	7.95 [< .001]	4.25	1.40 [±.51]	1.80 [±.86]	2.10 [.054]	1.12
Digit Span Fwd	7.53 [±0.64]	7.73 [±0.59]	1.87 [.082]	1.00	6.93 [±1.10]	6.40 [±1.30]	−2.48 [.027]	1.33
Digit Span Bwd	5.93 [±1.10]	6.47 [±0.92]	1.84 [.088]	0.98	5.20 [±1.08]	5.07 [±0.96]	−.62 [.546]	0.33
CERAD Imm Recall	25.67 [±3.31]	27.67 [±2.53]	3.37 [.005]	1.80	24.60 [±2.26]	25.27 [±2.63]	1.30 [.215]	0.69
CERAD Del Recall	8.27 [2.02]	9.53 [±0.92]	3.30 [.005]	1.76	8.27 [±1.16]	8.40 [±1.50]	.41 [.685]	0.22
Digit Symbol	31.73 [±5.05]	36.47 [±4.50]	8.03 [< .001]	4.29	31.67 [±6.14]	33.60 [±6.20]	2.21 [.044]	1.18
Verbal Fluency	19.27 [±4.93]	19.20 [±5.47]	−.064 [.950]	0.34	16.93 [±4.85]	16.47 [±6.20]	−.44 [.664]	0.23
Raven's SPM	16.33 [±3.81]	17.00 [±3.89]	.59 [.563]	0.32	15.93 [±4.13]	15.87 [±3.13]	−.071 [.944]	0.04
LPS	18.53 [±3.85]	20.93 [±3.08]	2.79 [.015]	1.49	19.73 [±4.30]	20.73 [±3.69]	1.23 [.238]	0.66

Note: [1]Mean values indicate number of correct items, except in *n*-back: achieved difficulty level.
[2]LPS Figural Relations Test: young training group ($n = 14$).

FIGURE 3. Mean values and standard deviations of achieved difficulty level as a function of training session, separately for old and young training groups and control groups.



the two training groups (age group by time ANOVA), younger training participants showed higher training gains than older training participants, $F(1, 28) = 51.61$, $MSE = 153.60$, $p < .001$, $\eta_p^2 = .648$. *Post-hoc t*-tests are reported in Table 2a, b.

Transfer effects

To investigate transfer effects in younger and older participants, 2 (training vs. control group) × 2 (t1 vs. t2) ANOVAs were conducted for each of the neuropsychological tests in younger and older participants separately. A transfer effect was defined as a significant group by time interaction, when the training group increases more than the control group in the performance of a given test.

To compare the gains of the two training groups within each of the transfer tasks, we performed 2 (young training group vs. old training group) × 2 (t1 vs. t2) ANOVAs for each test. Results from *post-hoc t*-tests analyzing the test gains for each of the four groups separately, are reported in Table 2a, b. Statistical values of the ANOVAs are shown in Table 3.

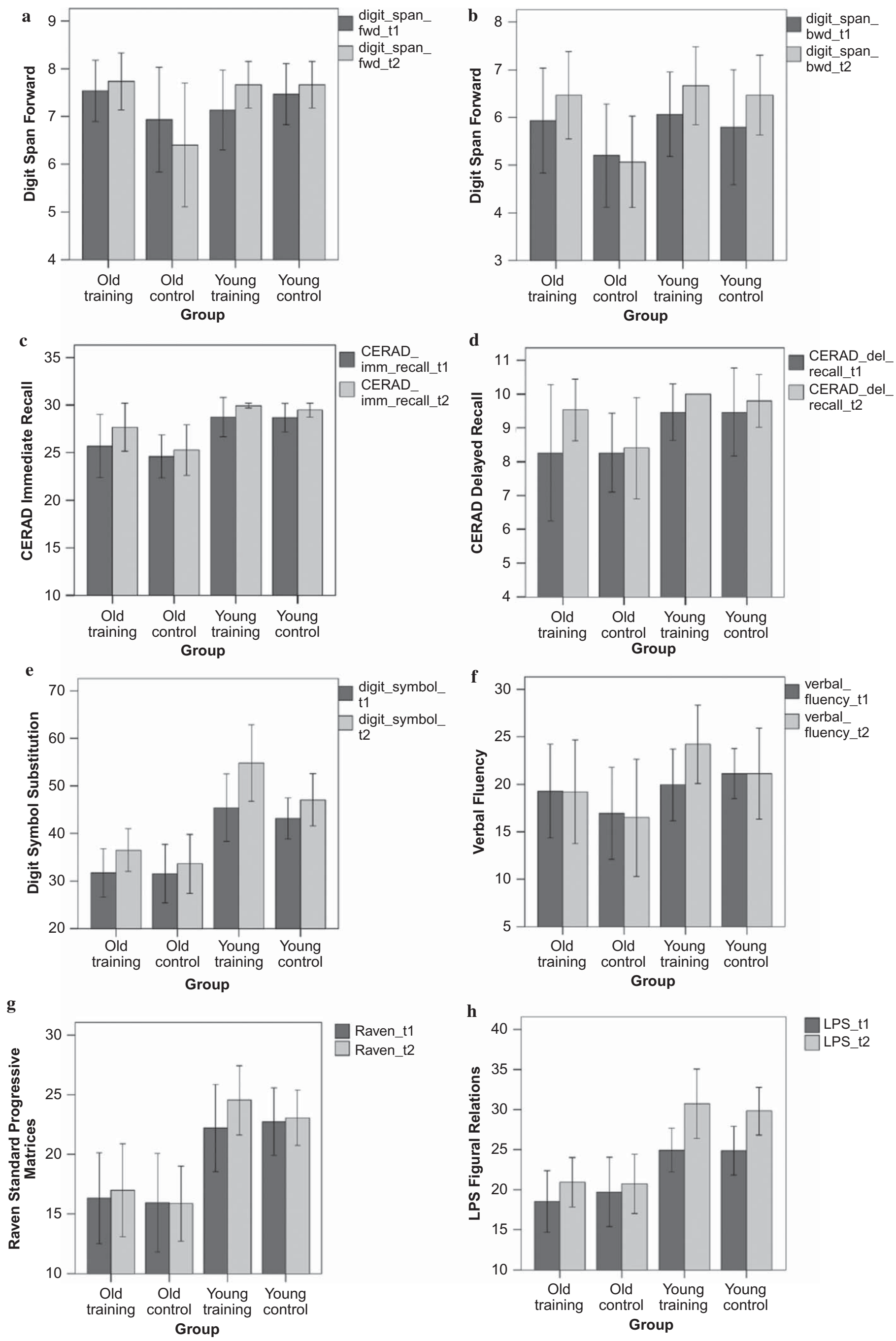
Short-term memory: Digit Span

In Digit Span Fwd (Figure 4a), the group (training vs. control) by time (t1 vs. t2) interaction was not significant in younger participants, $F(1, 28) = 1.65$, $MSE = 0.42$, $p = .209$, $\eta_p^2 = .056$, but in older participants, F(1,

TABLE 3. *F*-values, *p*-values, and η_p^2 of 2 (group) × 2 (time) analyses of variance of the *n*-back task and the neuropsychological measures

	ANOVA: group (young training vs. young control) × time (t1 vs. t2)			ANOVA: group (old training vs. old control) × time (t1 vs. t2)			ANOVA: group (young training vs. old training) × time (t1 vs. t2)		
Tasks	*F*-value	*p*-value	η_p^2	*F*-value	*p*-value	η_p^2	*F*-value	*p*-value	η_p^2
n-Back level	148.84	< **.001**	.842	44.02	< **.001**	.611	51.61	< **.001**	.648
Digit Span Fwd	1.65	**.209**	.056	9.31	**.005**	.249	1.92	**.176**	.064
Digit Span Bwd	0.05	**.826**	.002	3.40	**.076**	.108	.04	**.843**	.001
CERAD Imm Recall	0.37	**.548**	.013	2.89	**.100**	.093	1.05	**.315**	.036
CERAD Del Recall	0.56	**.461**	.020	5.12	**.032**	.155	2.78	**.107**	.090
Digit Symbol	8.27	**.008**	.228	5.84	**.022**	.172	7.69	**.010**	.216
Verbal Fluency	5.55	**.026**	.165	0.07	**.788**	.003	5.99	**.021**	.175
Raven's SPM	2.83	**.104**	.092	0.25	**.620**	.009	1.47	**.235**	.050
LPS	0.40	**.534**	.015	1.40	**.246**	.048	5.93	**.022**	.180

FIGURE 4. Mean values and standard deviations of the four groups before (t1) and after (t2) training/waiting period for (a) Digit Span Forward (Digit Span Fwd), (b) Digit Span Backward (Digit Span Bwd), (c) CERAD Immediate Recall (CERAD Imm Recall), (d) CERAD Delayed Recall (CERAD Del Recall), (e) Digit Symbol Substitution test (Digit Symbol), (f) Verbal Fluency test (Verbal Fluency), (g) Raven's Standard Progressive Matrices (Raven's SPM), and (h) LPS Figural Relations test (LPS).



28) = 9.31, MSE = 2.02, p = .005, η_p^2 = .249. When comparing the two training groups, no significant differences between younger and older training participants were found, $F(1, 28) = 1.92$, $MSE = 0.42$, $p = .176$, $\eta_p^2 = .064$. In Digit Span Bwd, no significant group by time interactions were detected in younger, $F(1, 28) = 0.05$, $MSE = 0.02$, $p = .826$, $\eta_p^2 = .002$, and older participants, $F(1, 28) = 3.40$, $MSE = 1.67$, $p = .076$, $\eta_p^2 = .108$. Also, no differences between the two training groups were found, $F(1, 28) = 0.04$, $MSE = 0.02$, $p = .843$, $\eta_p^2 = .001$. Results from *post-hoc t*-tests are reported in Table 2a, b.

Episodic memory: Immediate and Delayed Recall

In the CERAD Imm Recall, no significant group by time interactions were found in younger, $F(1, 28) = 0.37$, $MSE = 0.60$, $p = .548$, $\eta_p^2 = .013$, and older participants, $F(1, 28) = 2.89$, $MSE = 6.67$, $p = .100$, $\eta_p^2 = .093$. Also, comparing the two training groups revealed no significant differences, $F(1, 28) = 1.05$, $MSE = 2.40$, $p = .315$, $\eta_p^2 = .036$, see Figure 4c.

While the group by time interaction in younger participants was not significant in CERAD Del Recall, $F(1, 28) = 0.56$, $MSE = 0.15$, $p = .461$, $\eta_p^2 = .020$, older training participants showed higher gains in this task compared to the older control group, $F(1, 28) = 5.12$, $MSE = 4.82$, $p = .032$, $\eta_p^2 = .155$. No difference between younger and older training groups was found, $F(1, 28) = 2.78$, $MSE = 2.02$, $p = .107$, $\eta_p^2 = .090$. Results are shown in Figure 4d.

Processing speed: Digit Symbol

The comparison between the younger training and the younger control group, $F(1, 28) = 8.27$, $MSE = 112.07$, $p = .008$, $\eta_p^2 = .228$, and the comparison between the older training and the older control group, $F(1, 28) = 5.84$, $MSE = 26.67$, $p = .022$, $\eta_p^2 = .172$, showed significant group by time interactions, see Figure 4e. The results indicate that both training groups can improve their performance in the Digit Symbol task. Greater improvements were found in younger compared to older training participants, $F(1, 28) = 7.69$, $MSE = 81.67$, $p = .010$, $\eta_p^2 = .216$.

Executive functions: Verbal Fluency

A significant group by time interaction was only found in younger adults, $F(1, 28) = 5.55$, $MSE = 68.27$, $p = .026$, $\eta_p^2 = .165$, indicating improved performance in the Verbal Fluency test in the younger training group compared to the younger control group (see Figure 4f). The comparison between older training and control participants, $F(1, 28) = 0.07$, $MSE = 0.60$, $p = .788$, $\eta_p^2 = .003$, indicated that the performance gains from t1 to t2 did not differ significantly between the two groups. Higher improvements in the Verbal Fluency task were found in the younger compared to older training group, $F(1, 28) = 5.96$, $MSE = 70.42$, $p = .021$, $\eta_p^2 = .175$.

Fluid intelligence: Raven's SPM and LPS

No significant group by time interactions were found for Raven's SPM (see Figure 4g) in younger, $F(1, 28) = 2.83$, $MSE = 15.00$, $p = .104$, $\eta_p{}^2 = .092$, and older participants, $F(1, 28) = 0.25$, $MSE = 2.02$, $p = .620$, $\eta_p{}^2 = .009$. Also, no differences in performance gain were found between younger and older training groups, $F(1, 28) = 1.47$, $MSE = 10.42$, $p = .235$, $\eta_p{}^2 = .050$.

When analyzing the LPS Figural Relations test (see Figure 4h), no significant group by time interactions were found in younger, $F(1, 28) = 0.40$, $MSE = 2.63$, $p = .534$, $\eta_p{}^2 = .015$, and older, $F(1, 28) = 1.40$, $MSE = 7.35$, $p = .246$, $\eta_p{}^2 = .048$. However, younger training participants showed higher performance gains than older training participants, $F(1, 28) = 5.93$, $MSE = 41.50$, $p = .022$, $\eta_p{}^2 = .180$.

DISCUSSION

Training gains in *n*-back

In the current study, we found that after 12 training sessions, healthy younger participants were able to improve their performance in an *n*-back working memory task up to difficulty level 12 (includes 4-back condition at an interstimulus interval of 1600 ms), while older participants did not exceed difficulty level 5 on average (includes 2-back condition at an interstimulus interval of 1000 ms). The average difficulty level younger participants achieved after 12 sessions (4-back) is comparable to the results reported by Jaeggi et al. (2008). In our study, the majority of the older participants were unable to perform 3-back at a hit rate of above 80% after 4 weeks of training. This finding is in line with research from Li et al. (2008). Li and colleagues showed that the performance of older participants in a 3-back task does not exceed 80% accuracy even after 45 training sessions. It seems that through training, differences between younger and older adults in working memory performance are magnified (see also Loevdén, Brehmer, Li, & Lindenberger, 2012).

Transfer effects

In addition to substantial training effects in the *n*-back task, we found significant transfer effects in several non-trained cognitive tasks. Apart from a common transfer effect to Digit Symbol, domains of transfer differed between younger and older participants. Younger participants showed a transfer to Verbal Fluency, whereas in older participants, a transfer to Digit Span Fwd and CERAD Del Recall was found.

The comparison between younger and older training participants showed that performance gains differed between age groups in Digit Symbol, Verbal Fluency and LPS. Younger training participants were found to improve more in these tasks than older ones.

Transfer to short-term memory

A near transfer to Digit Span Fwd in older participants is in line with previous working memory training studies (Borella et al., 2010; Brehmer et al., 2012). The working memory training may have improved their short-term memory storage capacity as discussed in a recent meta-analytic review on working memory training and transfer by Melby-Lervåg and Hulme (2013). Surprisingly, no transfer to Digit Span Bwd was found in older participants. The group by time interaction in this task was only significant on a trend level ($p = .076$), therefore statistical power of the current study may have been too low to detect a transfer effect in this task.

In the current study, we did not detect a transfer to either of the two Digit Span tasks in younger participants. This finding may be due to profound ceiling effects. In Digit Span Fwd the maximum length of the digit lists was 8 digits and in Digit Span Bwd the maximum length was 7 digits. In Digit Span Fwd, 14 out of 30 (in Digit Span Bwd, 11 out of 30) younger participants were already able to master the most difficult task level at t1. Therefore, possible further improvement could not be detected by the test at t2 for these participants.

Transfer to episodic memory

A similar ceiling effect occurred in the CERAD Del Recall task. While older training participants showed improvements in this task, no changes were detectable in the younger participants. This is very likely due to the fact that 20 out of 30 younger participants had already achieved the highest possible score of 10 correct items at t1. Thus, conclusions about the influence of working memory training on performance in episodic memory in younger participants cannot be drawn from the current data. As only 8 out of 30 older adults achieved the maximum performance at t1, results in older participants seem to be less affected by ceiling effects (see Figure 4d). The significant transfer effect in this age group indicates that working memory training led to improved episodic memory performance (see also Buschkuehl et al., 2008; Richmond et al., 2011; Schmiedek et al., 2010).

Contrary to our hypothesis, no transfer effects in CERAD Imm Recall were found in either age group. This lack of transfer in younger participants may again be explained by ceiling effects. In older participants however, significant improvements in the training group ($p = .005$) together with no changes in the control group ($p = .234$) in this task may suggest that a potential interaction effect was not detected due to the small sample sizes. Therefore, future studies should involve more difficult versions of this task and include larger samples.

Transfer to processing speed

The finding of a transfer effect in Digit Symbol for both age groups suggests that our *n*-back working memory training program led to an improvement in processing speed performance. Possibly, the successive reduction of the interstimulus interval forced participants to focus on increasing their speed when responding to target stimuli. This interpretation is supported by findings from Takeuchi et al. (2011) using the method of reducing the interstimulus interval to train processing speed. However, since no active control group that was training on a low-speed level, was included, we cannot be sure that improvements in Digit Symbol result from the adaptive manipulation of the interstimulus interval. Since good working memory abilities were found to be related to Digit Symbol performance (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002), it is possible that gains in Digit Symbol were also directly related to an improved working memory performance. This could explain why younger training participants showed greater improvement in this task than older ones. In our study design, working memory and speed training were confounded; therefore it is not possible to disentangle the influence of these two components on transfer tasks. Future studies should address this problem by comparing different training regimes that focus on either speed or working memory training.

Transfer to executive functions

Transfer to Verbal Fluency was restricted to younger participants in the current study. This result may be due to the large difference in achieved difficulty levels in the training task between the two training groups. On average, younger participants trained at much higher and more executively demanding difficulty levels than older participants. The *n*-back training procedure might have improved the ability to inhibit certain word categories (e.g., proper names) in Verbal Fluency.

However, since our working memory training procedure included processing speed training, improvement in this cognitive domain may have also affected Verbal Fluency performance because this task requires the production of words during a very limited amount of time (60 seconds).

Older participants showed less training-related improvement in the *n*-back and Verbal Fluency tasks compared to younger participants. These findings may support the concept that age-related differences in executive control (for review, see Verhaeghen & Cerella, 2002) may be magnified through training (Loevdén et al., 2012). As Verbal Fluency only covers certain aspects of executive functions (Larsson et al., 2007), additional tests measuring executive functions would be very useful to adequately examine transfer effects to this cognitive domain in future studies.

Transfer to fluid intelligence

Contrary to our hypothesis, no transfer to our speeded tasks of fluid intelligence (LPS Figural Relations Test and Raven's SPM) was found in the current study.

Our findings of no transfer to fluid intelligence add to the ongoing debate on the trainability of intelligence (Redick et al., 2012; Shipstead et al., 2012; Slagter, 2012; Sternberg, 2008). Although theoretically plausible, empirical evidence of transfer from working memory training to fluid intelligence has been very inconsistent (Shipstead et al., 2012). Some studies have reported transfer (Borella et al., 2010; Jaeggi et al., 2008; Karbach & Kray, 2009; Klingberg et al., 2005) while many others have not (Chooi & Thompson, 2012; Dahlin, Nyberg, et al., 2008; Holmes, Gathercole, & Dunning, 2009; Redick et al., 2012; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009; Westerberg et al., 2007). To date, it is unclear which parameters of the training procedure enable participants to improve their performance in fluid intelligence tasks. Since studies that have reported transfer to fluid intelligence tend to involve executively demanding tasks (e.g., dual working memory: Jaeggi et al., 2008; task-switching: Karbach & Kray, 2009), it may be speculated that if transfer to fluid intelligence is possible at all, it requires training tasks that are specifically demanding on executive functions.

LIMITATIONS AND FUTURE RESEARCH

Some methodological limitations should be considered when interpreting the findings of the current study. First, the study sample was relatively small. Therefore, results should be replicated using larger samples. Second, only passive control groups were tested. The possibility that social engagement or motivation associated with the training procedure had a beneficial effect on performance in several tasks cannot be ruled out. Due to the lack of active control groups, we cannot be sure about which mental processes were actually trained in our study. From the design of our study, it is not possible to conclude whether training on working memory or processing speed was the active ingredient that led to gains in non-trained tasks. Specifically, our hypothesis of boosting transfer to processing speed and other tasks by manipulating the interstimulus interval in our working memory task needs to be proven in future studies by including an active control group that practices on a low speed level. In order to disentangle working memory training from speed training, groups that train on either speed or working memory only need to be included in future studies. Third, as no follow-up analyses were conducted in the current study, no conclusions about the temporal stability of the observed training and transfer effects can be made at this point. Fourth, since we observed strong ceiling effects in CERAD Recall and the Digit Span tasks, more difficult versions of these tasks should be used in future studies to rule out this problem.

CONCLUSION

The current study investigated the effects of a novel approach to adaptive training of working memory in younger and older adults as well as transfer to other cognitive tasks that were selected to represent different cognitive processes. Digit Span Fwd and Digit Span Bwd were selected as proxies for short-term memory, CERAD Imm Recall and CERAD Del Recall for episodic memory, Digit Symbol for processing speed, Verbal Fluency for executive functions, and LPS and Raven's SPM for fluid intelligence. While both younger and older adults were able to improve their working memory performance through an *n*-back training procedure, younger participants showed much larger training gains. Transfer to Digit Symbol and Verbal Fluency tasks was found in the younger training group. The older training group showed transfer to Digit Span Fwd, CERAD Del Recall, and Digit Symbol. Thus, the results of the present study indicate that far transfer is possible in older age and working memory training may be a beneficial intervention to maintain and improve cognitive functioning at all stages of life.

Original manuscript received 21 December 2012
Revised manuscript received 21 March 2013
First published online 2 May 2013

REFERENCES

Acevedo, A., & Loewenstein, D. A. (2007). Nonpharmacological cognitive interventions in aging and dementia. *Journal of Geriatric Psychiatry and Neurology*, *20*, 239–249.

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2005). Working memory and intelligence: The same or different constructs? *Psychological Bulletin*, *131*, 30–60.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*, 417–423.

Baddeley, A., & Hitch, G. (1974). Working memory. In G. Bower (Ed.), *Recent advances in learning and motivation* (Vol. 8, pp. 47–90). New York, NY: Academic Press.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., . . . Willis, S. L. (2002). Effects of cognitive training interventions with older adults: A randomized controlled trial. *JAMA: The Journal of the American Medical Association*, *288*, 2271–2281.

Baltes, P. B., Sowarka, D., & Kliegl, R. (1989). Cognitive training research on fluid intelligence in old age: What can older adults achieve by themselves? *Psychology and Aging*, *4*, 217–221.

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin*, *128*, 612–637.

Benton, A. L., & Hamsher, K. (1989). *Multilingual Aphasia Examination*. Iowa City, IA: AJA Associates.

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: A meta-analysis. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *60*, P223–P233. doi:10.1093/geronb/60.5.P223

Borella, E., Carretti, B., Riboldi, F., & De Beni, R. (2010). Working memory training in older adults: Evidence of transfer and maintenance effects. *Psychology and Aging*, *25*, 767–778.

Braver, T. S., & West, R. (2008). Working memory, executive control, and aging. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (3rd ed., pp. 311–372). New York, NY: Psychology Press.

Brehmer, Y., Westerberg, H., & Baeckman, L. (2012). Working-memory training in younger and older adults: Training gains, transfer, and maintenance. *Frontiers in Human Neuroscience*, *6*, 63. doi:10.3389/fnhum.2012.00063

Buckner, R. L. (2004). Memory and executive function in aging and AD: Multiple factors that cause decline and reserve factors that compensate. *Neuron*, *44*, 195–208.

Bunting, M. F., Conway, A. R., & Heitz, R. P. (2004). Individual differences in the fan effect and working memory capacity. *Journal of Memory and Language*, *51*, 604–622.

Burgaleta, M., & Colom, R. (2008). Short-term storage and mental speed account for the relationship between working memory and fluid intelligence. *Psicothema*, *20*, 780–785.

Burgess, N., & Hitch, G. (2005). Computational models of working memory: Putting long-term memory into context. *Trends in Cognitive Sciences*, *9*, 535–541. doi:10.1016/j.tics.2005.09.011

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Daepp, C., Mueller, M., . . . Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychology and Aging*, *23*, 743–753. doi:10.1037/a0014342

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review*, *97*, 404–431. doi:10.1037/0033-295X.97.3.404

Carretti, B., Borella, E., Zavagnin, M., & de Beni, R. (2012). Gains in language comprehension relating to working memory training in healthy older adults. *International Journal of Geriatric Psychiatry*. doi:10.1002/gps.3859

Carroll, J. B. (1993). *Human cognitive abilities*. Cambridge: University Press.

Chen, T., & Li, D. (2007). The roles of working memory updating and processing speed in mediating age-related differences in fluid intelligence. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *14*, 631–646.

Chooi, W.-T., & Thompson, L. A. (2012). Working memory training does not improve intelligence in healthy young adults. *Intelligence*, *40*, 531–542. doi:10.1016/j.intell.2012.07.004

Clay, O. J., Edwards, J. D., Ross, L. A., Okonkwo, O., Wadley, V. G., Roth, D. L., & Ball, K. K. (2009). Visual function and cognitive speed of processing mediate age-related decline in memory span and fluid intelligence. *Journal of Aging and Health*, *21*, 547–566. doi:10.1177/0898264309333326

Cohen, J. D., Forman, S. D., Braver, T. S., Casey, B. J., Servan-Schreiber, D., & Noll, D. C. (1993). Activation of the prefrontal cortex in a nonspatial working memory task with functional MRI. *Human Brain Mapping*, *1*, 293–304.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, *30*, 163–183. doi:10.1016/S0160-2896(01)00096-4

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*, 547–552.

Dahlin, E., Neely, A. S., Larsson, A., Baeckman, L., & Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science*, *320*, 1510–1512.

Dahlin, E., Nyberg, L., Baeckman, L., & Neely, A. S. (2008). Plasticity of executive functioning in young and older adults: Immediate training gains, transfer, and long-term maintenance. *Psychology and Aging*, *23*, 720–730.

D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature*, *378*, 279–281.

Doumas, M., Rapp, M. A., & Krampe, R. T. (2009). Working memory and postural control: Adult age differences in potential for improvement, task priority, and dual tasking. *Journal of Gerontology*, *64*, 193–201.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology. General*, *128*, 309–331.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198.

Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews. Neuroscience*, *13*, 491–505. doi:10.1038/nrn3256

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience*, *6*, 316–322.

Greenwood, P. M. (2007). Functional plasticity in cognitive aging: Review and hypothesis. *Neuropsychology*, *21*, 657–673.

Guenther, V. K., Schaefer, P., Holzner, B. J., & Kemmler, G. W. (2003). Long-term improvements in cognitive performance through computer-assisted cognitive training: A pilot study in a residential home for older people. *Aging & Mental Health*, *7*, 200–206.

Hertzog, C., Kramer, A. F., Wilson, R. S., & Lindenberger, U. (2008). Enrichment effects on adult cognitive development can the functional capacity of older adults be preserved and enhanced? *Psychological Science in the Public Interest*, *9*(1), 1–65. doi:10.1111/j.1539-6053.2009.01034.x

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, *12*, F9–15.

Horn, W. (1983). *Leistungspruefsystem LPS (2. Aufl.)*. Goettingen: Hogrefe.

Intraub, H. (1980). Presentation rate and the representation of briefly glimpsed pictures in memory. *Journal of Experimental Psychology: Human Learning and Memory*, *6*(1), 1–12. doi:10.1037/0278-7393.6.1.1

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 6829–6833.

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science*, *12*, 978–990.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, *14*, 317–324.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstroem, K., . . . Westerberg, H. (2005). Computerized training of working memory in children with ADHD – A randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*, 177–186.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence*, *14*, 389–433.

Larsson, M. R., Michel, P., Baeckstroem, M., & Johanson, A. (2007). Baseline verbal fluency performance as predictor of state anxiety during a live hand-grenade throwing exercise –

A prospective study of Swedish military conscripts. *Behavioral and Brain Functions*, *3*, 39.

Li, S., Schmiedek, F., Huxhold, O., Roecke, C., Smith, J., & Lindenberger, U. (2008). Working memory plasticity in old age: Practice gain, transfer, and maintenance. *Psychology and Aging*, *23*, 731–742.

Loevdén, M., Brehmer, Y., Li, S.-C., & Lindenberger, U. (2012). Training-induced compensation versus magnification of individual differences in memory performance. *Frontiers in Human Neuroscience*, *6*, 141. doi:10.3389/fnhum.2012.00141

Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: A review and future directions. *Neuropsychology Review*, *19*, 504–522. doi:10.1007/s11065-009-9119-9

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, *49*, 270–291. doi:10.1037/a0028228

Morris, J. C., Heyman, A., Mohs, R. C., Hughes, J. P., van Belle, G., Fillenbaum, G., . . . Clark, C. (1989). The Consortium to Establish a Registry for Alzheimer's Disease (CERAD). Part I. Clinical and neuropsychological assessment of Alzheimer's disease. *Neurology*, *39*, 1159–1165.

Noack, H., Loevdén, M., Schmiedek, F., & Lindenberger, U. (2009). Cognitive plasticity in adulthood and old age: Gauging the generality of cognitive intervention effects. *Restorative Neurology and Neuroscience*, *27*, 435–453. doi:10.3233/RNN-2009-0496

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., . . . Ballard, C. G. (2010). Putting brain training to the test. *Nature*, *465*, 775–778. doi:10.1038/nature09042

Park, D. C., & Payer, D. (2006). Working memory across the adult lifespan. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 128–142). New York, NY: Oxford University Press.

Peng, H., Wen, J., Wang, D., & Gao, Y. (2012). The impact of processing speed training on working memory in old adults. *Journal of Adult Development*, *19*, 150–157. doi:10.1007/s10804-012-9142-6

Penner, I.-K., Vogt, A., Stöcklin, M., Gschwind, L., Opwis, K., & Calabrese, P. (2012). Computerised working memory training in healthy adults: A comparison of two different training schedules. *Neuropsychological Rehabilitation*, *22*(5), 716–733. doi:10.1080/09602011.2012.686883

Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. G., & Kokmen, E. (1999). Mild cognitive impairment: Clinical characterization and outcome. *Archives of Neurology*, *56*, 303–308.

Proctor, R. W. (1983). Recognition memory for pictures as a function of poststimulus interval: An empirical clarification of existing literature. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 256–262. doi:10.1037/0278-7393.9.2.256

Rajah, M. N., & D'Esposito, M. (2005). Region-specific changes in prefrontal function with age: A review of PET and fMRI studies on working and episodic memory. *Brain*, *128*, 1964–1983.

Raven, J., Summers, B., & Birchfield, M. (1990). *Manual for raven's progressive matrices and vocabulary scales. Research supplement no. 3: A compendium of North American normative and validity studies*. Oxford: Oxford Psychologists Press.

Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., . . . Engle, R. W. (2012). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology. General*. doi:10.1037/a0029082

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*, 177–182. doi:10.1111/j.1467-8721.2008.00570.x

Reuter-Lorenz, P. A., & Park, D. C. (2010). Human neuroscience and the aging mind: A new look at old problems. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *65B*, 405–415. doi:10.1093/geronb/gbq035

Richmond, L. L., Morrison, A. B., Chein, J. M., & Olson, I. R. (2011). Working memory training and transfer in older adults. *Psychology and Aging*, *26*, 813–822. doi:10.1037/a0023631

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.

Schmiedek, F., Loevdén, M., & Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: Findings from the COGITO study. *Frontiers in Aging Neuroscience*, *2*, 1–10.

Shelton, J. T., Elliott, E. M., Matthews, R. A., Hill, B. D., & Gouvier, W. D. (2010). The relationships of working memory, secondary memory, and general fluid intelligence: Working memory is special. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *36*, 813–820.

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*, *138*, 628–654. doi:10.1037/a0027473

Slagter, H. A. (2012). Conventional working memory training may not improve intelligence. *Trends in Cognitive Sciences*. doi:10.1016/j.tics.2012.10.001

Sternberg, R. J. (2008). Increasing fluid intelligence is possible after all. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 6791–6792. doi:10.1073/pnas.0803396105

Takeuchi, H., Taki, Y., Hashizume, H., Sassa, Y., Nagase, T., Nouchi, R., & Kawashima, R. (2011). Effects of training of processing speed on neural systems. *Journal of Neuroscience*, *31*, 12139–12148. doi:10.1523/JNEUROSCI.2948-11.2011

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, *12*, 106–113.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience and Biobehavioral Reviews*, *26*, 849–857.

Verhaeghen, P., & Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological Bulletin*, *122*, 231–249.

von Bastian, C. C., Langer, N., Jäncke, L., & Oberauer, K. (2012). Effects of working memory training in young and old adults. *Memory & Cognition*. doi:10.3758/s13421-012-0280-7

Wechsler, D. (1987). *Wechsler memory scale – revised: Manual*. San Antonio, TX: Psychology Corporation.

Westerberg, H., Jacobaeus, H., Hirvikoski, T., Clevberger, P., Ostensson, M., Bartfai, A., & Klingberg, T. (2007). Computerized working memory training after stroke – A pilot study. *Brain Injury*, *21*, 21–29.

Willis, S. L. (1990). Current issues in cognitive training research. In E. A. Lovelace (Ed.), *Aging and cognition: Mental processes, self-awareness, and interventions. Advances in psychology*, *72*. Oxford: North-Holland.

Wright, A. A., Cook, R. G., Rivera, J. J., Shyan, M. R., Neiworth, J. J., & Jitsumori, M. (1990). Naming, rehearsal, and interstimulus interval effects in memory processing. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *16*, 1043–1059.

Zelinski, E. M. (2009). Far transfer in cognitive training of older adults. *Restorative Neurology and Neuroscience*, *27*, 455–471. doi:10.3233/RNN-2009-0495

Zimprich, D., & Martin, M. (2002). Can longitudinal changes in processing speed explain longitudinal age changes in fluid intelligence? *Psychology and Aging*, *17*, 690–695.

Zinke, K., Zeintl, M., Eschen, A., Herzog, C., & Kliegel, M. (2012). Potentials and limits of plasticity induced by working memory training in old-old age. *Gerontology*, *58*, 79–87. doi:10.1159/000324240