The Effects of Aging and Physical Fitness on Working Memory Capacity[*]

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Previous studies indicate that physical fitness plays a protective role against age-related cognitive decline (e.g., Colcombe & Kramer, 2003). Using event-related potentials (ERPs), we investigated age-related cognitive decline in working memory processing and whether physical fitness positively influences working memory capacity in older adults. Data from 13 younger and 25 older adults (tested for their physical fitness) were analyzed. The participants performed a modified Sternberg memory search task while ERPs were recorded. The memory set was presented in upper-case letters, with a memory set size varying from 2 to 6. A lower-case probe letter following the memory set required a positive ("old") or negative ("new") response. Behavioral data showed age-related but not fitness-related differences. The ERPs, elicited by the memory set, showed (a) an age effect in the posterior P1 component, and (b) age and fitness effects in the frontal negativity. These results suggest that age affects general working memory processes, but physical fitness may help specifically to reduce the decline of working memory capacity.

Key words : aging, physical fitness, working memory capacity, event-related potentials(ERPs), frontal negativity

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Subjective memory complaints are common in older adults. However, upon questioning, they often express difficulty not with long-term memory, but with tasks requiring the maintenance of information in a brief period of time. Aging research has found that older adults do have specific declines in this type of cognition, generally known as working memory (Park et al., 1996; Fabiani & Wee, 2001; Fabiani, 2012). Park et al. (1996) showed that working memory (measured by computation span, reading span, and backward digit span tasks) declines steadily throughout the lifespan starting in young adulthood. This decline in older adults is not purely behavioral, as brain degeneration may be linked to this kind of cognitive decline (Raz, 1997, 2002). For example, Raz (2002) found dramatic decline in brain volume and increased tissue atrophy with age, correlated with cognitive decline in older adults (Raz, 1997). Particularly, the prefrontal cortex is susceptible to volume loss with age (e.g., Raz, 1997; Raz et al., 2010) and is a crucial node for working memory processes (Narayanan et al., 2005).

Although cognitive and neurobiological research on aging may paint a bleak picture about normal aging, studies over the past several decades have shown that physical fitness (particularly associated with cardiac functioning) can slow down age-related cognitive decline in humans (e.g., Hawkins et al., 1992; Kramer et al., 1999; Colcombe & Kramer, 2003; Colcombe et al., 2004; Gordon et al., 2008; Fabiani & Gratton, 2009). For example, Hawkins and colleagues (1992) found positive effects of exercise on dual-task performance for older adults who underwent a 10-week exercise program compared to those who did not. Moreover, some studies have found that brain activity changes as cardiopulmonary function improves, reflecting fitness-induced cognitive changes (e.g., Dustman et al., 1990; Trejo et al., 2001; Hillman et al., 2002; Colcombe et al., 2004; Themanson & Hillman, 2006).

For instance, Colcombe and colleagues (2004) used a flanker task (Eriksen & Eriksen, 1974) that requires attentional control and response inhibition. Older adults participated in two separate studies, comparing (a) high-fit (HF) and low-fit (LF) older adults and (b) those trained in six-month cardiovascular and strength exercise interventions. Not only did both the HF and cardiovascular exercised older adults show reduction in interference behaviorally, but they also showed greater prefrontal and parietal recruitment of brain regions (involved in spatial selection and inhibitory functioning) and less anterior cingulate activity (associated with conflict monitoring) than the LF and strength-trained older adults in functional magnetic resonance imaging responses. These results indicate that

top-down attentional control accompanying reductions in response conflict was increased for the older adults who were physically fit and had improved cardiac functions compared to their counterparts. Themanson and Hillman (2006) reported that the error-related negativity (ERN; Gehring et al., 1993; Falkenstein et al., 1991) was smaller for HF than for LF older adults. The ERN is known to be generated in or near the anterior cingulate cortex (e.g., Dehaene et al., 1994) and reflects response conflict (Yeung et al., 2004). Thus, this result is in line with the reduced activation in the anterior cingulate cortex for conflict trials observed by Colcombe et al. (2004).

According to a meta-analysis (Colcombe & Kramer, 2003), these fitness-induced benefits in aging are largest for executive-control processes. Because working memory is an essential part of executive-control processes, fitness-induced benefits should be observed in working memory tasks. Thus, the present study focused on fitness-induced benefits of working memory in age-related cognitive decline using a direct measure of brain activity, event-related brain potentials (ERPs; Fabiani et al., 2007). Specifically, we focused on the amount of information held for a brief period of time (i.e., working memory capacity). Using a Sternberg memory search task, some studies compared response times (RTs), including their slopes and intercepts estimated

across different set-sizes before and after elderly participants underwent aerobic and anaerobic exercise training programs (Blumenthal & Madden, 1988; Madden et al., 1989). They did not find any significant differences in these measures between the two training programs. Sternberg (1969) hypothesized that a RT slope reflects the speed of memory comparison processes, and a RT intercept reflects stimulus encoding and response selection processes. It is possible that physical fitness may not directly influence these types of processes, but may more directly affect the amount of information held active in memory. In fact, Strayer and colleagues (1987) and Basak and Verhaeghen (2003) have shown that speed of scanning or access to items within the focus of attention is relatively intact with age.

We examined the modulation of the frontal negativity as a function of memory set-sizes shown to participants of different ages and fitness levels. Ruchkin and colleauges (1990) fou nd that the amplitude of a left frontal negativity (also known as the anterior negativity) increased as memory load became larger during a retention interval between memory set and probe, independently of preparation processes (Ruchkin et al., 1995). These results suggest that the frontal negativity reflects retention and rehearsal of encoded memory items (Ruchkin et al., 1994), and is sensitive to memory load.

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Thus, we examined this negativity, observed at frontal midline location, as a function of age and fitness in the context of different working memory loads. We were particularly interested in fitness effects: If physical fitness positively influences on capacity-limited working memory storage, then we will find different patterns of frontal negativity across different set-sizes as a function of fitness scores. Presumably, older adults with higher fitness scores may show increased amplitudes of the frontal negativity with increasing set-sizes, similarly to younger adults (Ruchkin et al., 1990, 1994, 1995). Conversely, older adults with lower fitness scores may have a smaller frontal negativity than those with higher fitness scores, especially at larger set-sizes.

We additionally examined the effects of age and fitness on the ability to process multiple visual items. The posterior, visually evoked P1 component is a positive deflection peaking around 100 ms poststimulus and generated in extrastriate cortex (Di Russo et al., 2001; Hillyard & Anllo-Vento, 1998). Typically, the P1 is larger for stimuli shown in attended locations than for those shown in unattended locations (Mangun & Hillyard, 1991; Eimer, 1994), reflecting an attention-related sensory gain control that is activated for the improvement of the acuity of visual perception (Eimer 1993, 1994; Mangun & Hillyard, 1991). Thus, the P1

represents a facilitation of early perceptual processes, supporting early selection of visuospatial information (Heinze et al., 1990; Luck et al., 1990; Mangun & Hillyard, 1991). As other cognitive abilities, the ability to process visuospatial information also declines with age (e.g., Jenkins et al., 2000). Czigler and Bal ázs (2005) found that sensory-evoked P1 responses to simultaneously presented multiple stimuli decreased with age, regardless of the target relevance of the stimuli. This suggests that an early sensory facilitation for multiple visual stimuli shown in an attended area is ineffective in older adults. Thus, we expect that upon the presentations of larger memory-set items, P1 decreases should be more evident in older than in younger adults. Moreover, if fitness effects are evident at these early perceptual stages, older adults with higher fitness should have more efficient gain control than those with lower fitness. In other words, larger positivity would indicate a facilitation of encoding processes. Thus, HF older adults may show larger P1 amplitudes even in larger set-size conditions than LF older adults.

Methods

Participants   Participants were recruited in the Champaign-Urbana community, USA. Sixteen younger (age 18-25, 7 women) and thirty-two

older adults (age 65-86, 15 women) participated in this study after going through the screening procedures described below. The older adults were tested for their cardiovascular fitness levels, which were reflected in individual VO_2max scores. Three younger and seven older participants were excluded from data analyses due to ERP recording errors, resulting in a total of 13 younger and 25 older participants. To account for normative gender differences in VO_2max scores, we used a median split of VO_2max scores within each gender for this grouping, generating a stratified sample. We divided the older participants into HF and LF individuals only to describe and display our results (see Table 1 and Figures 1 and 2). Table 1 shows the demographic data for the younger and the HF and LF older adults. These data indicate that the HF group was significantly younger than the LF group, $t(23) = 2.11$, $p <$ 0.05. Hence, we entered age and gender along with VO_2max scores as predictors for regression analyses whenever fitness effects were tested within the older adults. All participants signed informed consent and were paid $15 per hour for their participation.

Screening Procedures The participants recruited for the study all passed the following inclusion criteria: (a) native speakers of English; (b) normal or corrected-to-normal vision; (c) right-handedness (as assessed by Edinburgh Handedness Inventory, Oldfield, 1971); (d) no previous history of psychiatric disorders or head trauma; (e) no use of prescription drugs or medications that are known to affect the central nervous system (e.g., neuroleptic, antidepressant, anxiolytic agents, and beta blockers); (f) a minimum score of 51 on the modified Mini-Mental Status Exam (Mayeux et al., 1981); (g)

Table 1. Mean scores characterizing the demographic information of the participants. Standard deviations are in parentheses.

Measures	Young (N=13; 6 men)	Older (N=25; 15 men)	HF older (N=13; 8 men)	LF older (N=12; 7 men)
Age (yr)	23 (2)	71 (5)	70 (4)	74 (6)
Education (yr)	16 (2)	16 (3)	16 (3)	17 (4)
VO2max(mL/kg-1/min)	--	25 (7)	29 (6)	21 (4)
mMMSE	57 (1)	55 (2)	55 (2)	56 (1)

HF = high-fit; LF = low-fit

yr = years

mMMSE = Modified Mini-Mental Status Exam score

no signs of depression on Beck's Depression Scale (Beck et al., 1996); (h) within one standard deviation of the average score for their age group on the Vocabulary subtest of the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981).

Fitness Assessment A maximal graded exercise test was used to assess the cardiorespiratory functioning in older participants. The test measures maximal aerobic power (VO_2 max) obtained by the following procedure: Participants walked on a motor-driven tread mill at a speed of 3mph with increasing grade increments of 2% every 2 minutes while their expired gases were sampled every 30 seconds using the ParvoMedics Inc. TrueMax 2400 metabolic system. The test was terminated either by objective evidence indicating that maximal oxygen uptake (VO_2max) had been reached or by volitional exhaustion on the participant's side. Heart rate and blood pressure were monitored during the test by continuous 12-lead electrocardiography, auscultation, and sphygmomanometer.

Stimuli and Task The stimuli were the alphabet letters B, D, F, G, H, J, M, R, and T, which have different shapes when displayed in upper and lower case. Each trial consisted of a memory set presented in upper case and a

single letter probe presented in lower case. The size of the memory set varied, ranging from 2 to 6 letters, presented simultaneously in a row right above fixation in the center of the screen for 3000 ms. Each letter horizontally and vertically subtended approximately $0.95°$ of visual angle, and letters were separated by $0.19°$ of visual angle. Thus, the entire memory set subtended from $2°$ (for set-size 2) to $6.68°$ (for set-size 6) of visual angle. The increasing set-size increased perceptual and working memory loads.

After a fixation interval of 1000 ms, the memory set was followed by the presentation of a probe, which was displayed for 500 ms at the center of the screen right above the fixation cross (which remained on the screen during the entire task). The next memory set was presented 1500 ms after the offset of the probe. Participants were asked to respond to each letter probe as quickly and accurately as they could. The membership of the probe in the memory set determined the hand to use. Thus, if the probe was part of the memory set (requiring a "Yes" response), they pressed one of two buttons on a response box with one hand. If the probe was not part of the memory-set (requiring a "No" response), they responded by pressing the other button with the other hand. The time allowed for responding was 1900 ms. The hands assigned to yes (i.e., positive) and no (i.e., negative) responses were counterbalanced across

participants.

The letters making up the memory set were randomly selected, with the constraint that no identical letter should be presented within the same memory set. On half of the trials, the probe was one of the letters in the memory set, and hence the ratio of positive to negative responses was 1:1. Twenty blocks of 32 trials were run per day (i.e., one session), with a break after the first 10 blocks. Memory set size was fixed within a block but varied between blocks. During the first 10 blocks of trials, memory sets were presented either in an ascending-to-descending (i.e., set-sizes 2, 3, 4, 5, 6, 6, 5, 4, 3, and 2) or a descending-to-ascending (i.e., set-sizes 6, 5, 4, 3, 2, 2, 3, 4, 5, and 6) order. This order was repeated one more time during the second 10 blocks for each participant, and the assignment of this order was counterbalanced across participants.

Participants were asked to fixate their eyes on the central fixation cross and to limit body and eye movements throughout the experiment. In addition, we emphasized that participants should refrain from rehearsing the memory set letters vocally or mouthing the letters to minimize artifacts generated by mouth movements. To be certain, we monitored participants using a closed-circuit television while they performed the task. We discouraged them from vocalizing or mouthing the memory set items when such an

attempt was observed.

ERP Recording The electroencephalogram (EEG) was recorded using a limited electrode montage,[1] including four midline scalp sites (Fz, Cz, Pz, and Oz) as well as the left and right mastoids. Individually placed Grass gold electrodes were used for all electrophysiological recordings. The left mastoid was used as the on-line reference, but an average mastoid reference was derived off-line for analysis. In each session, two of the midline electrodes (either Fz-Pz or Cz-Oz) were recorded. The order of this recording was counterbalanced across participants. In addition to this counterbalancing, we also tested whether the order of the recording (from Fz-Pz in session 1 and Cz-Oz session 2 or vice versa) generated any systematic influences on the P1 and the frontal negativity. Results showed no systematic differences in these component measurements, $Fs(1, 36) < 2.32$, ns in all cases. The vertical and horizontal electrooculogram (EOG) was also recorded using bipolar derivations (based on

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1) The electroencephalogram (EEG) was recorded simultaneously with the event-related optical signal (EROS; Gratton & Fabiani, 2001, 2010) throughout two separate sessions. The EROS neuroimaging method, in which optic fibers are placed on extensive scalp areas, limited EEG recording sites. For the present paper, we will be focusing on reporting our ERP results and will not discuss the portions related to the EROS.

electrodes placed above and below the right eye for the vertical EOG and 2 cm outside the left and right canthi for the horizontal EOG.

A 0.01-30 Hz band-pass filter was used for all electrophysiological recordings. Electrode impedance was kept below 10 KOhm. EEG and EOG were sampled continuously across a block at 100 Hz[2]. The data were segmented off-line (using a 200-ms pre-stimulus baseline and a 2800 ms post-stimulus period), anchored on memory set onset.

Data Reduction and Analysis

Ocular artifacts in the raw EEG data were corrected using a procedure described by Gratton et al. (1983). All trials with potentials exceeding 200 μV or with EEG exceeding the A/D range in any of the channels were considered to contain artifact-related activity and were excluded from further analyses. ERP waveforms were then averaged for each participant, electrode, and condition. Only trials on which the participants responded correctly were used for the analysis.

As noted in the introduction, we focused on two ERP components: the posterior P1 and the frontal negativity. To quantify the P1, we calculated the mean amplitude of the average

ERP waveform at the Oz site between 150 and 200 ms after memory set onset for each participant and memory set size. To determine set-size effects, we averaged smaller set-sizes (2 and 3) and larger set-sizes (5 and 6) separately, and subtracted the smaller set-sizes from the larger set-sizes for each participant. This memory load difference was analyzed using a regression analysis in which age was entered as a predictor. For the frontal negativity, we measured the mean amplitude of the average waveforms obtained at the Fz site within a time window between 250 and 800 ms post-stimulus for each participant and each set-size condition. We then computed linear and quadratic slopes of these mean amplitudes across the five set-sizes, separately for each participant. We also computed slopes based on low (set-size 2 to 4) and high (set-size 4 to 6) loads separately and then calculated the difference between the low and high load slopes, separately for each participant. We then conducted a regression analysis for each dependent variable (i.e., linear and quadratic slopes, and difference between high and low load slopes). For the computation of the effects of age these three dependent variables were regressed on age only. For the computation of the effects of fitness we conducted stepwise multiple regressions, in which age, VO $_2$max, and gender were included, in order to determine the best predictor(s) of the

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2) The sampling rate 100 Hz is adequate for testing the effects of the P1 and the frontal negativity in this study because these effects were derived from differences in amplitude and activity pattern rather than in peak or latency.

activity of the frontal negativity.

Results

Behavior Table 2 summarizes the behavioral results. Positive and negative responses were significantly different for RTs (788 ms and 884 ms, respectively; $F[1, 370] = 62.24$, $p < 0.001$) and accuracy (0.93 and 0.96, respectively; $F[1, 37] = 17.37$, $p < 0.001$). Also, there was a significant interaction between response type and set-size in RTs, $F(4, 148) = 28.34$ $p < 0.001$, indicating that RTs increased less with set-size for the positive than for the negative responses. Because we were primarily interested in changes in the set-size effects on RTs and accuracy as a function of age and fitness, we collapsed data from the positive and negative responses for all further analyses. As shown in Table 2, RTs increased approximately linearly with set-sizes in the three groups. Slopes assessing the memory search rate (Sternberg, 1969) were calculated for each individual across all set-sizes (2-6) as well as across only low (2-4) and high (4-6) set-sizes, to measure the impact of high and low memory loads on memory search rate. The search rate difference did not show any meaningful correlation with age, $r = -0.08$, $n.s.$, and was not predicted by any of the variables (i.e., age, fitness, and gender) as revealed by a stepwise multiple regression. These results suggest that the speed of memory scanning was similar for all participants. However, accuracy showed an

Table 2. Reaction times and accuracy across set-sizes in the young, high-fit (HF) and low-fit (LF) older groups. Standard deviations are in parentheses.

	Reaction Times			Accuracy		
	Young (N=13)	HF older (N=13)	LF older (N=12)	Young (N=13)	HF older (N=13)	LF older (N=12)
set-size 2	578 (66)	809 (147)	776 (140)	0.97 (0.03)	0.97 (0.02)	0.99 (0.01)
set-size 3	626 (75)	867 (146)	846 (146)	0.96 (0.03)	0.97 (0.03)	0.98 (0.01)
set-size 4	677 (81)	925 (170)	915 (154)	0.95 (0.02)	0.95 (0.04)	0.97 (0.02)
set-size 5	726 (84)	983 (156)	988 (161)	0.94 (0.04)	0.92 (0.07)	0.94 (0.03)
set-size 6	778 (81)	1022 (144)	1054 (159)	0.90 (0.06)	0.87 (0.05)	0.88 (0.05)

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interaction between age and set-size. Although accuracy decreased with the set-sizes in all participants, older adults tended to drop more rapidly as the set-size became larger, indicating that high memory loads negatively affected older more than younger adults. This pattern was corroborated by a significant correlation between the difference slope and age, $r = 0.38$, $p < 0.05$.

Electrophysiology As shown in Figure 1, the P1 component exhibited similar amplitudes for the young adults whether the set-size was larger or smaller. However, older adults (regardless of fitness) showed smaller P1 amplitudes for high loads than for low loads. These visual impressions were supported by a significant relationship between age (but not fitness) and load effects on the P1 component, $b = 0.37$, $p < 0.05$.

Figure 2 displays the grand-average waveforms obtained at the Fz site in the three groups. First, the young participants' waveforms appear to be more negative than the older participants' waveforms. This observation was supported by a significant correlation between age and mean amplitudes measures of the frontal negativity, $r = 0.35$, $p < 0.05$. Moreover, whereas the younger participants had similar frontal negativity amplitudes across the different

A. Grand-average waveforms by high and low memory loads

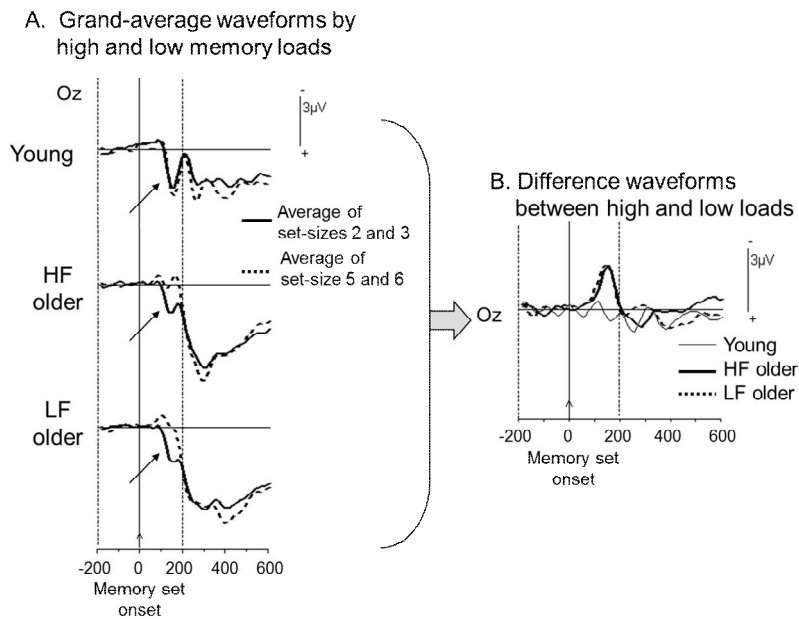B. Difference waveforms between high and low loads

Figure 1. A: Grand-average waveforms from Oz computed separately for the low load (set-sizes 2-3) and high load (set-sizes 5-6) conditions for the young, high-fit (HF) and low-fit (LF) older participants. The arrows point to the P1 component. B: Difference waveforms obtained by taking the difference between the low and the high load displayed in Figure 1A. Note that negativity is plotted up.
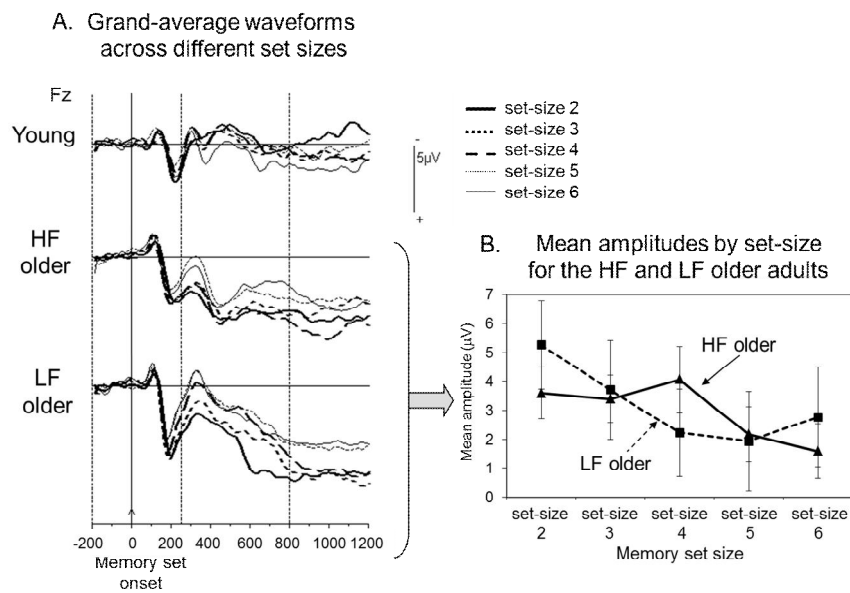
Figure 2. A: Grand-average waveforms obtained at the Fz site across the different set-sizes for each group. B: Mean amplitudes of the grand-average waveforms at the Fz site taken within a time-window between 250 and 800 ms (approximated by the dotted lines) after memory set onset for the HF and LF older adults. Note that the division of the HF and LF older adults was made for the purpose of displaying fitness effects visually. The actual statistical analysis treated fitness as a continuous variable.

set-sizes, the older had frontal negativities that differed substantially as a function of set-sizes in the same time window, with amplitude progressively larger (i.e., more negative) with increasing set-size. This different pattern of ERP amplitudes between the younger and older participants was tested by a regression analysis, in which linear slope estimates of the frontal negativity by set-size function were regressed on age, $\beta = -0.39$, $p < 0.05$.

Interestingly, the older adults showed a clear split at the set-size 4 as a function of fitness levels (see, Figure 2B): The LF older adults showed similar amplitudes at set-sizes 4, 5, and 6, and yet the HF older adults showed similar

amplitudes for the set-sizes 2, 3, and 4. A series of stepwise multiple regression analyses tested this difference, which was predicted by VO_2max scores (not by age or gender) when quadratic slope estimates were regressed, $\beta = -0.54$, $p = 0.01$. The difference between the slopes derived from high and low memory loads was also predicted by VO_2max scores, $\beta = -0.38$, $p = 0.06$. This fitness by load interaction for the frontal negativity is particularly interesting because it suggests that higher levels of physical fitness can result in the maintenance of a relatively large working memory capacity during aging.

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Discussion

Within the framework of encouraging reports suggesting beneficial effects of physical fitness on cognitive aging (e.g., Hawkins et al., 1992; Kramer et al., 1999; Colcombe & Kramer, 2003; Colcombe et al. 2004), the current study investigated effects of age and fitness on working memory capacity using the ERP method. Working memory is an important component in executive functions, which can be improved in older adults by intervention programs focusing on physical fitness (Colcombe & Kramer, 2003). Some previous studies relying solely on RT data failed to demonstrate fitness-induced benefits (Blumenthal & Madden, 1988; Madden et al., 1989). In contrast, the current study focused on examining the effects of fitness on working memory capacity in older adults as well as their ability to process multiple stimuli shown simultaneously in visual space. These manipulations probed whether fitness-induced benefits are specific or can be generalized across different cognitive abilities.

We found that RT slopes did not show any significant correlations with age or with fitness. Although accuracy declined considerably for the older adults as memory set-size increased, fitness was not predictive of the increasing set-size effect on accuracy in the older adults. These results support the ideas that (a) the memory search rate within the focus of attention is relatively intact with age (Strayer et al., 1987; Basak et al., 2003), as well as with physical fitness (Blumenthal & Madden, 1988; Madden et al., 1989); however, (b) there may be age-related working memory deficits, related to reductions in memory span.

Unlike these behavioral results, ERPs showed both age and fitness effects. During the encoding of the memory set, the younger adults showed similar P1 amplitudes across the different set-sizes. However, the older adults showed different P1 amplitudes, with smaller P1s at larger set-sizes. These results indicate that when the amount of incoming sensory information becomes large, the ability to select and encode that information is weakened in older adults. In other words, this suggests that an appropriate amplification of attended early sensory information is diminished in older adults, especially when a large amount of information is present. Lindenberger and Baltes (1994) demonstrated that decreased sensory function may be related to cognitive difficulties in older adults. However , a follow-up study (Lindenberger et al., 2001) concluded that peripheral changes in sensory acuity do not account for the connection between sensory and cognitive functioning. Neurobiological changes occurring at the central level, such as atrophy in the cerebral cortex and reductions in blood flow in the brain

may be important to explain cognitive aging. In this sense, cardiopulmonary fitness may play a role in moderating cognitive aging.

Here, we found that the frontal negativity elicited after memory set onset was more negative in the younger than in the older adults. It has been suggested that the frontal negativity reflects memory retention/rehearsal processes (Ruchkin et al., 1990; 1994; 1995). Some investigators (e.g., Vos et al., 2001) made use of the frontal negativity to investigate available working memory capacity. More broadly slow negative brain potentials hae been associated with resource allocation (e.g., Rösler et al., 1997). The current results for the frontal negativity may be related to the notion that older adults have difficulty in voluntarily recruiting necessary resources, unless explicit assistance provided by cues or by explicit task instructions that encourage efficient task strategies (Craik & Simon, 1980; Park et al., 1990). Logan and colleagues (2002) noted that older adults tended to show less activation in brain regions, associated with particular cognitive processes or tasks than younger adults. They tested this under-recruitment phenomenon with and without giving participants explicit deep (semantic) encoding instructions. With deep elaboration encoding, older adults showed increased activity in left frontal regions, statistically comparable to that observed in younger adults in the same regions.

It appears that effective resource allocation is tightly related to the use of efficient task strategies. We not only found age-related differences in the amplitudes of the frontal negativity, but also different patterns of set-size effects for the younger and older participants. The waveforms were very similar across set-sizes in the younger adults, but different as a function of VO$_2$max scores in the older adults. It is possible that the younger participants adopted more efficient strategies (e.g., chunking, semantic/deep encoding) during encoding, which could have led them to minimize the number of items being maintained. Conversely, the older participants may not have adopted efficient encoding strategies (Fabiani et al., 2006), leading them to difficulties due to limitations in their working memory capacity.

Interestingly, fitness differentially affected memory load, as shown by the significant quadratic slope difference. In particular, set-size 4 appears to be an important break point, at which the performance of HF and LF older adults separated, as evidenced by the significant difference slope. These results suggest that HF older adults may have larger working memory capacity than LF older adults. Many investigators have shown that 3 to 5 items could be held in a capacity-limited working memory storage, and that there are age and individual differences in

that storage system (for review, Cowan, 2001; see also, Schneider-Garces et al., 2010). The present study demonstrated that physical fitness positively influenced the number of items that can be maintained within the focus of attention.

One thing to note is that this fitness effect was not evident in behavior. This discrepancy may be due to two possibilities. First, this cognitive benefit may not yet have transferred into a behavioral benefit. Perhaps, more practice time or a larger effect may be required for this cognitive difference to be manifested behaviorally. Second, the RT data obtained from each set-size were more appropriate for measuring memory search rate than for estimating working memory capacity. In fact, we introduced the frontal negativity to the current study due to this reason. As a result, we found that fitness effects in working memory in older adults are more specific to capacity than to processing speed, which is reflected in the discrepancy between the frontal negativity and RT results.

We do not know the precise origin(s) of this component. However, it is reasonable to think that the prefrontal cortex may be the main source of this ERP component, given that many primate and neuroimaging studies showed a strong involvement of the prefrontal cortex during working memory tasks (e.g., Goldman-Rakic, 1992; Rypma & D 'Esposito, 2000). Furthermore, little is known as to the exact

causal relationships linking healthy cerebrovascular function, healthy brain tissue volumes, and intact working memory processes. Animal studies report an increase in neurotrophic factors (such as brain-derived neurotrophin factor, insulin-like growth factor 1, and serotonin), and improved neuroplasticity and cell survival with aerobic exercise (Berchtold et al., 2001; Carro et al., 2001; Cotman & Berchtold, 2002). Correlations between neurogenesis and increased cerebral blood volume in the dentate gyrus have also been reported in exercising mice (Pereira et al., 2007). Although most studies in animals and humans have shown that increased cardiovascular fitness is beneficial to the brain, a more complete understanding of these factors needs to be pursued in further research.

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노화와 노인의 신체 건강이 작업 기억에 주는 효과

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기존의 많은 연구들이 신체 건강(physical fitness)이 노화 관련 인지 저하에 맞서 보호적 기능을 한다고 지적하였다(예, Colcombe & Kramer, 2003). 본 연구에서는, 구체적으로 작업 기억의 처리과정에서 노화가 미치는 인지 기능에 대한 영향과 신체 건강이 노인들의 작업 기억 용량에 긍정적인 영향을 끼치는 지에 관하여 사건관련전위(ERP)를 이용하여 연구하였다. 13명의 청년과 신체 건강 검사를 마친 25명의 노인들이 스턴버그 기억 추적 과제를 수행하였다. 이 과제에서 영문 알파벳이 자극으로 이용되었는데 크기 2-6까지 중 한 크기의 기억 세트(memory set)가 대문자로 먼저 제시된 후 소문자 글자 하나가 시험자극(probe)으로 제시되었다. 이에 실험 참가자는 시험자극이 기억 세트의 일부 자극이었는지 그렇지 않은지를 판단하였다. 행동적으로는 연령 차이에 따른 효과가 있었으나 신체 건강 효과는 관찰되지 않았다. 기억 세트의 크기에 따른 사건관련전위 결과는 기억 세트 제시 이후 P1 컴포넌트에서 연령 차이가 두드러졌고, 전두성 부적전위(frontal negativity)에서는 나이와 신체 건강 효과가 함께 나타났다. 이러한 결과는 노화가 작업 기억의 전반적인 과정에 영향을 미치나, 신체 건강이 작업 기억 용량의 저하를 완화시켜준다는 점을 시사한다.

주요어 : 노화, 신체 건강, 작업 기억 용량, 사건관련전위, 전두성 부적전위