體育學報
中華民國體育學會
第 49 卷第 S 期，頁 75～90 (2016. 6.)
DOI:10.3966/102472972016064900S006

Effects of aerobic training intensity on executive functions in middle-to-old age adults

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Abstract

The beneficial effects of physical exercise, especially aerobic training, on cognitive functions in middle or old age adults have been demonstrated in a sizable amount of recent studies. However, the majority of these research works mainly contrasts the difference between the training and the non-training control groups. Hence their results only reflect the pre- vs. post-training difference between groups "with" and "without" training, and do not reveal the training effect parametrically. The current study aims to investigate how aerobic training with different intensity influences executive functions in middle-to-old age people. Two groups of middle-to-old adults were recruited and randomly assigned to a low-intensity (40% HRR) and a moderate intensity (60% HRR) group for a 12-week cyclic ergometer training program. Tests for components of executive functions, including shifting, inhibition, and updating, were administered immediately before, during, and immediately after the training program. We found that moderate intensity training effectively enhanced physical fitness, in terms of six-minute walking distance, to a larger extent than low intensity. Among the three components of executive function, only the mixing cost of task-switching showed dependence on training intensity in terms of both acute and long-term effect. In conclusion, intensity of aerobic training does not uniformly modulate all components of executive function.

Key words: executive functions, aerobic exercise, training intensity

Introduction

A sizable amount of recent empirical findings have demonstrated that training on physical exercise improves cognitive abilities across various group of age and cognitive/ neurological status (Erickson & Kramer, 2009; Etnier & Chang, 2009; Etnier, Noerll, Landers, & Sibley, 2006; Hung & Shih, 2009; Kramer & Hillman, 2006; McAuley et al., 2007; Winter et al., 2007; Tsai, 2009; Chuang, Huang, & Hung, 2014; Chang, Chu, Wang, & Yang, 2013; Chang & Wu, 2011). Accumulating evidence indicates

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that physical exercise results in improvement of cognitive abilities to no less, if not a greater, extent than direct training on these abilities (Colcombe & Kramer, 2003; Hillman, Weiss, Hagberg, & Hatfield, 2002; Hogan, 2005; Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Kramer & Erickson, 2007; Reynolds et al., 2003). Given the evidence that physical exercise not only improves our physical health but also our mental capacity, the nature of this "fitness effect" has elicited vast interests among many related disciplines such sport scientists, psychologists, and cognitive neuroscientists.

As promising as it sounds, one has to note that training of physical exercise (PE-training) does not always lead to improvement on behavioral measures of cognitive abilities. These negative findings included reaction time (Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004) and/or accuracies (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman et al., 2002). As pointed out by Kramer (2007), several factors could potentially influence whether PE-training leads to improvement on cognitive functions: 1. the manner in which cardiorespiratory fitness was characterized from resting heart rate to the gold standard, VO_2 max; 2. the length, duration and intensity of exercise training; 3. the cognitive processes examined in the studies; and 4. the age, health, sex and fitness levels of participants.

Among the substantial variability in participants involved and experimental designs adopted in studies examining the influence of exercise on cognition (see Colcombe & Kramer, 2003; Etnier et al., 2006; Heyn, Abreu, & Ottenbacher, 2004; Chang, Labban, Gapini, & Etnier., 2010; Smith et al., 2011; Chang et al., 2013; Chang & Wu, 2011 for comprehensive reviews), the current study is particularly interested in the effect of aerobic exercise on the executive functions of the middle-to-old age adults. The reason is that adults of this age cohort start to or already experience the threat of aging-related cognitive deterioration, and that executive functions are highly related to the frontal lobe which is among the brain structures most vulnerable to the negative impacts of aging (Reuter-Lorenz & Slvester, 2005). Understanding life-style factors reducing the threat from cognitive and brain aging to executive functions, such as physical exercise, could be of tremendous value in facilitate successful aging.

Executive function can be broadly defined as a collection of control processes that are responsible for monitoring and manipulating on-line mental activities. In keeping with this main theme, a few different ways of fractionizing executive functions have been proposed (Miyake et al., 2000; Repovs & Baddeley, 2006; Jurado & Rosselli, 2007; Oberauer, Suss, Schulze, Wilhelm, & Wittmann, 2000; Smith & Jonides, 1999), and it is generally agreed that the following subcomponents of executive functions crucial for maintaining one's online mental activities, namely (a) *shifting* between mental sets, (b) inhibition of dominant or proponent responses, and (c) *updating and monitoring* of working memory representations (Baddeley, 1996; Miyake et al., 2000; Smith & Jonides, 1999). While moderate effect size of chronic exercise training on executive function have been reported (in an ostensibly non-differentiated manner) (Liu-Ambrose & Eng, 2015; Nouchi et al., 2014; Voss et al., 2010; Masley, Weaver, Peri, & Phillips, 2008; Scherder et al., 2005; Wallman, Morton, Googman, Grove, & Guilfoyle, 2004; Khatri et al., 2001; Emery et al., 1998), no study has systematically compared how different subcomponents of executive function are modulated by exercise training. Therefore, it is timely to examine how chronic aerobic exercise differentially influences subcomponents of executive functions to advance our understanding of the nature of fitness effect.

In terms of the exercise training protocol, there have been fairly sparse controlled and randomized investigations parametrically examining important mediating factors such as exercise intensity (Tsai et al., 2014; Kamijo, Nishinira, & Higashura, 2009; Chang & Etnier, 2009), session duration (Chang et al., 2015), session frequency, and program duration (Voss et al., 2010). Using exercise intensity as an example, because the majority of chronic training study merely contrast the difference between training and non-training control groups, their results only reflect the pre- vs. post-training difference between groups “with” and “without” training, and do not reveal dose-response effects (Liu-Ambrose & Eng, 2015; Nouchi et al., 2014; Voss et al., 2010; Masley et al., 2008; Scherder et al., 2005; Wallman et al., 2004; Khatri et al., 2001; Emery et al., 1998). To date, the dose-response relationship between exercise intensity and cognitive function has been explored mainly for acute resistance exercise (Chang & Etnier, 2009; Brown & Bray, 2015; Chang et al., 2011; Chang & Etnier, 2013) and acute aerobic exercise (Smiley-Oyen, Lowry, Francois, Kohut & Ekkekakis, 2008), but not for chronic training studies.

Parametric implementation of exercise training factors, such as intensity, session duration, and program duration, has tremendous values in understanding the nature of the fitness effect as well as adaptively optimizing training programs. For example, with a parametric manipulation of the intensity of acute resistance exercise (High, moderate, and low intensities), Chang and Etnier (2009) found that there is a significant linear effect of exercise intensity on information processing speed, and a significant quadratic trend for exercise intensity on executive function, which suggests the dose-response relationship depends on both the exercise intensity and the cognitive function studied.

Given the paucity of empirical work elucidating dose-response characteristics for long-term exercise training as well as how the acute and long-term exercise training are conjointly influenced by training intensity or other training factors (cf. Audiffren & Andre, 2015), the aims of the current study is thus two-folded: 1) To compare the effects of long-term and acute bout of aerobic exercise training on executive functions at different training intensities; 2) to examine how different components of the central executive function are modulated by aerobic exercise training.

Methods

Participants. Forty middle-to-old age adults (44-75 years old) were recruited after screening for health conditions. All participants are from the neighborhood communities of National Central University. They were recruited after being screened for cognitive and fitness tests. Only participants in good mental and physical health are qualified for the training program. Participants are assigned to groups that are trained in two different intensities (40% or 60% of HRR). Originally all demographic variables were equivalent. However, as the training progressed, drop-off resulted in inequivalent group size, average age and digit span between groups. The basic demographic information and cognitive/fitness measurements across time points are listed in Table 1.

Table 1.

Demographic information, cognitive abilities, and fitness level of the two training groups

Training Intensity		Moderate	Low
Sample Size		20	18
Gender		14F, 6M	13F, 5M
Age		58.4± 5.3	61.4± 6.2
Digit Span[a]	Week1	19.1± 1.0	16.9± 1.1
	Week12	18.2± 1.1	17.8± 1.2
RAPM	Week1	11.4± 1.9	10.8± 1.9
	Week6	12.2± 1.9	12.0± 2.0
	Week12	9.7± 1.9	10.9± 2.0
6-min Walking (meters)	Week1	537 ±10	524 ±10
	Week6*	705 ±25	620 ±27
	Week12*	73 8±16	68 2±18

Note. T1, T2, and T3 indicate week 1st, 6th, and 12th, respectively. Asterisks indicate significant difference between groups at the same testing time point. [a]Due to limited time of administration, digit-span was not tested at the 6th week.

Aerobic exercise training program: The training program was a 12-week aerobic exercise training on cyclic ergometer. The participants rode the ergometer 3 times per week, and 30 minutes (not including the warm-up and cool-down period) each time at one of the prescribed heart rates (40% and 60% of heart rate reserve [HRR]), depending on the intensity group assigned. The HRR was calculated using the Karvonen method (Strath et al., 2000) based on the resting heart rate measured during the screening session prior to the training program (also see Erickson et al., 2011), and the maximum heart rate was assumed to be 220 - age. These two training intensities were adopted based on the cut-off values of Light and Moderate Intensities described in Norton et al. (2010), and the general physical conditions of the participants during the screening session. During each training session, exercise intensity was monitored by readouts on a Polar heart rate (HR) monitor (RS400, Finland) outfitting the participant, and every participant was attended by their own coach[1] who reminded the participant to speed up or slow down their pace on the cyclic ergometer according to the instant HR, and inquired their subjective rating of physical exertion on the Borg scale every 5 minute during the 30 minutes training period. Figure 1 illustrates the schedule of training and cognitive assessments.

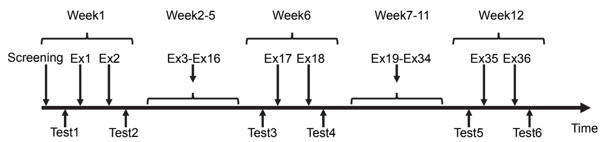

Figure 1. Schedule of the training program. Ex<n> indicates the nth exercise training session. Test<n> indicates the nth cognitive assessment. The whole training and assessment program last for 12 weeks. At Week 1st, 6th, and 12th, three pairs of cognitive assessments were arranged such that pre- and post-exercise assessment can be administered immediately before or after a bout of aerobic exercise training (namely, Test 1 vs. Test 2, Test 3 vs. Test 4, and Test 5 vs. Test 6) for examining the acute effect of aerobic exercise across different stage of the training program.

Assessment of physical fitness. All participants' physical fitness was assessed by 6-minute walking distance at the 1st, 6th, and 12th week from the beginning of the training program. The walking test was held indoor at the NCU gym circling a path marked by traffic cones.

[1] The group of coaches supporting the training program was recruited from the NCU swimming and basketball teams. They are student athletes who have received training on CPR and the protocol of the aerobic exercise in the current study.

Assessments of executive functions. Three subcomponents of the executive functions, including shifting, inhibition, and updating (Miyake et al., 2000), were assessed at the three periods of time as physical fitness. Unlike the measurement of physical fitness, the tests for executive functions were carried out twice at each testing point, one before a session of cyclic ergometer training and the other after, to compare the acute effect of aerobic training. The specific tasks used were a revised flanker task (adapted from Hazeltine, Poldrack, & Gabriell, 2000), the bivalent switching task (adapted from Karbach & Kray, 2009), and the visuospatial N-back task (adapted from Jaeggi, Busckuehl, Jonides, & Perrig, 2008). Note that although the shifting and inhibition components were measured with reaction time (RT), the focus in the current study was on the change of differences in RTs between conditions rather than the RTs per se. RT records the overall processing time required by completing each task, which could be the summation of perceptual, central executive, and motoric stages. Through careful design of the task, the difference between conditional RTs (e.g., mixing or switching costs in task switching) subtracts out the mutual perceptual and motoric stage shared by different conditions, and leaves only the processing time of the component (method of subtraction; Donders, 1868/1969)

Shifting component. The *shifting* component was tested by an *orientation/size judgement task*, in which participant either made judgement between horizontal and vertical orientation for the principle axis of an eclipse, or between big and small size by comparing the size of the eclipse to a standard circle shown at the beginning of the experiment. The task was administered in the following order: orientation block (30 trials), size block (30 trials), and finally mixed block (30 trials). In the mixed block, the orientation and the size trials were pseudo-randomly mixed such that 50% of the trials required the same type of judgement as their previous trial (repeated trials), while the other 50% required different judgement (switched trials).

Inhibition component. The *inhibition* component was assessed with a *Flanker task* revised from the conventional flanker paradigm (Eriksen & Schultz, 1979). Participants were required to respond as quickly and accurately as possible to a visual stimulus by pressing the appropriate key with the thumb. The stimulus correspond to three colored circles, horizontally arranged, which were presented in a known location immediately after a 1-s fixation point. Participants had to respond according to the color of the central circle (the target), while ignoring the color of the flanker circles (the distractors), which were presented simultaneously for 1-s on both sides of the target. There were be three levels of congruency in this task: 1) in the congruent condition (CO), the three circles were of the same color, and there was not any conflict at the sensory or the response level (32 trials); 2) in the sensory incongruent condition (SI), the target circle and the flanker circle was in different colors, which was supposed to induced interference at the sensory level, but correspond to the same response (16 trials); 3) in the response incongruent condition (RI), not only that the target and the flanker were in different colors, but they also required different responses, which was supposed to induced interference at both sensory and response levels (16 trials). As soon as a response key was pressed, the stimulus disappeared. When participants failed to respond within 1 second, the stimulus disappeared and the next trial began. The interval between the disappearance of the display and the onset of the next was 1 second.

Two types of interference, namely *sensory interference* and *response interference*, can be quantified by subtracting RTs between conditions: Difference RT between SI and CO conditions (i.e., RT_{SI}-RT_{CO}) indicate the delay induced by conflict in the sensory stage, whereas difference RT between RI and SI conditions (i.e., RT_{RI}-RT_{SI}) indicate the delay caused by conflict in the response stage.

Updating component. A N-back visuospatial memory task was adopted for evaluating the updating component. The participants monitored continuous streams of visual stimuli. Depending on the difficulty level, the current visual stimuli was the same as the Nth stimuli backwards in the streams. The participant had to detect the repetition and press a button when the visual and auditory targets occur simultaneously. The difficulty of the task increases with the size of N, and the size was adjusted adaptively according to the participant's performance with a 2-up-1-down staircase method. That is, N increased by one when the participant makes two consecutively correct responses and decrease by one when the participant makes an incorrect response. The task continued until 20+N trials or five deflections between increase and decrease of N have occurred, whichever condition was fulfilled first. The performance of each session of this task was quantified by weighted percentage accuracy across all levels of N.

Data analysis. To assess both the long-term and acute effects of exercise on the three computerized tests for subcomponents of executive function, these dependent measures were subject to linear mixed-effect (LME) model analyses, with Intensity (Moderate vs. Low), Testing Time (1^{st} week, 6^{th} week, and 12^{th} week), and Acute Stage (immediate pre- vs. immediate post-training) as fixed-effect factors, Age as a covariate, and subject as the random-effect factor. The mixed effect model has the advantage of being capable of including participants with missing data points in the analysis, which is valuable for longitudinal studies as a few of the participants may miss a few testing sessions during the lengthy training program but otherwise their performance was still informative. The LME model is as the following:

$$\text{DV} = \text{Intercept} + \text{Intensity} + \text{Testing Time} + \text{Acute Stage} + (\text{Intensity}\times\text{Testing Time}) + (\text{Intensity}\times\text{Acute Stage}) + (\text{Testing Time}\times\text{Acute Stage}) + (\text{Intensity}\times\text{Testing Time}\times\text{Acute Stage}) + \text{Age} + (1 \mid \text{Subject}) \quad \text{(Equation 1)}$$

where DV indicates dependent variable that could be one of the measures listed in Table 2 in an analysis. Other dependent variables that were not acquired with the Acute Stage factor were subject to linear mixed-effect model analyses with Intensity and Testing Time as the fixed-effect factors, Age as a covariate, and Subject as the random-effect factor:

$$\text{DV} = \text{Intercept} + \text{Intensity} + \text{Testing Time} + (\text{Intensity}\times\text{Testing Time}) + \text{Age} + (1 \mid \text{Subject}) \quad \text{(Equation 2)}$$

The fixed and random effects in the models were estimated with the Maximum Likelihood (ML) method via the MIXED procedure in SPSS (ver. 19; IBM Inc). Post hoc comparison was carried out with Student's t test and corrected for familywise error via Bonferroni correction.

In Equation 1 and 2, any interaction involving the Intensity factor indicates that training intensity modulated short-term or long-term cognitive performance. Specifically, the Intensity × Testing Time interaction indicates training intensity influences cognitive performance as the training program progressed from the 1st to the 12th week. The Intensity × Acute Stage interaction indicates training intensity impacts cognitive performance immediately through a single session of aerobic exercise. Finally, a significant three-way interaction suggests that magnitude of the immediate impact changed as the training program progressed.

Results

Fitness measures.

From Table 1, it is obvious that both groups of participants' 6-minute walking distance improved significantly across the 12-week training period (average of the two groups: 531, 662, and 709m at the 1st, 6th, and 12th week, respectively; $F(1, 29.21) = 5.83$, $p < .05$). Furthermore, there is a marginal tendency of Intensity × Testing Time interaction in that the Moderate intensity group improved more than the Low intensity group both at the 6th week (704 vs. 620m) and the 12th week (738 vs. 682m), but not at the 1st week (538 vs. 525 m), reflecting stronger change in aerobic fitness with higher training intensity ($F(2, 22.69)=2.90$, $p < .1$) as the training progressed.

Computerized tests on executive functions.

Task Switching (shifting component). Table 2 lists the single, repeat, switch RTs as well as the mixing cost and switching cost of task switching for both training intensities at each testing time point. All of these five dependent measures were subject to the linear mixed-effect model analysis specified in Equation 1. No significant effect was found for single RT. For the repeat RT, the effect of Acute Stage ($F(1, 20.935) = 10.284$, $p < .005$; pre- vs. post-training: 605 vs. 578ms), the Intensity × Acute Stage interaction ($F(1, 20.293) = 4.956$, $p < .05$), and the three-way interaction ($F(2, 32.596) = 3.844$, $p < .05$) reached significance. The three-way interaction was likely due to much longer repeat RT immediately before (652ms) than after (557ms) a single session of exercise at the 1st week for the moderate intensity group, but not for the low intensity group, and such group-specific acute effect was not observed for the 6th and 12th week.

For the switch RT, the effect of Acute Stage ($F(1, 19.520) = 20.015$, $p < .001$; pre- vs. post-training: 642 vs. 605ms) and the Intensity × Acute Stage interaction ($F(1, 19.526) = 7.394$, $p < .05$) were significant. The interaction was likely due to larger difference between pre- and post-training for the moderate (650 vs. 591ms) than for the low (634 vs. 619ms) intensity group.

For the mixing cost, significant factors include: Testing Time ($F(2, 19.675)$[2] $= 8.885$, $p < .005$), Acute Stage ($F(1, 23.968) = 7.435$, $p < .05$), Intensity×Acute Stage ($F(1,23.968) = 4.357$, $p < .05$), and the three-way interaction ($F(2, 18.90) = 4.559$, $p < .05$). For the Testing Time effect, post hoc tests found that mixing costs did not differ at the 1st week (61ms) and the 6th week (61ms), but significantly reduced at 12th week (37ms). The three-way interaction was due to that the Moderate Intensity group showed a

[2] Note that for the tests of fixed effects in the mixed-effect model, the denominator degrees of freedoms are not integers. This is because these statistics do not have exact F distributions. The denominator degrees of freedoms are obtained by a Satterthwaite approximation (SPSS technical document).

significant drop of mixing cost between the pre- and post-training tests at the 1st week but not at subsequent tests, whereas the Low Intensity group showed no significant acute changes at any time point. Finally, none of the effect for the switch cost approached significance.

Table 2.

Performance of the three computerized executive function tests.

Moderate Intensity						
Testing Time	Week 1		Week 6		Week 12	
Acute Stage	pre	post	pre	post	pre	post
RT_{Single}	542(18)	532(19)	521(22)	525(22)	531(27)	518(23)
RT_{Repeat}	652(29)	557(27)	599(28)	582(31)	586(28)	562(28)
RT_{Switch}	687(32)	577(29)	633(31)	610(38)	631(33)	587(32)
Mixing Cost	111(21)	25(17)	76(13)	57(16)	52(11)	40(10)
Switch Cost	36(11)	22(9)	33(8)	27(9)	45(7)	24(6)
RT_{CO}	735(28)	693(20)	713(24)	673(24)	688(29)	655(24)
RT_{SI}	789(26)	741(25)	727(25)	704(24)	735(29)	699(26)
RT_{RI}	793(30)	764(22)	745(23)	722(24)	718(27)	699(27)
$RT_{SI} – RT_{CO}$	45(19)	53(21)	27(12)	10(12)	43(13)	40(12)
$RT_{RI} – RT_{SI}$	26 (21)	6(19)	27(14)	27(13)	13(15)	0(12)
N-back (%)	66(5)	65(5)	65(6)	66(5)	79(6)	71(5)
Low Intensity						
RT_{Single}	558(19)	550(21)	538(22)	551(23)	564(28)	551(24)
RT_{Repeat}	604(31)	606(29)	601(29)	601(32)	588(30)	561(30)
RT_{Switch}	650(34)	646(31)	621 (32)	632(39)	631(35)	581(33)
Mixing Cost	45(22)	55(17)	54(13)	46(17)	29(12)	11(11)
Switch Cost	45(11)	36(10)	21(9)	28(9)	26(8)	10(6)
RT_{CO}	781(29)	756(21)	747(24)	706(25)	735(30)	711(26)
RT_{SI}	795(28)	787(26)	777(25)	702(25)	743(31)	745(28)
RT_{RI}	815(31)	797(23)	778(23)	711(25)	745(29)	749(29)
$RT_{SI} – RT_{CO}$	34(20)	18(22)	0(12)	34(12)	36(15)	6(13)
$RT_{RI} – RT_{SI}$	6(22)	17(20)	12(14)	2(13)	11(16)	7(13)
N-back (%)	61(6)	67(5)	68(6)	76(5)	77(6)	75(5)

Note. Values inside parentheses indicate SD. Mixing cost = RT_{Repeat}-RT_{Single}; switch cost = $RT_{Switch} – RT_{Repeat}$; sensory interference = $RT_{SI} – RT_{CO}$; response interference = $RT_{RI} – RT_{SI}$.

Flanker Task (Inhibition component). Table 2 lists the congruent, sensory incongruent, and response incongruent RTs as well as the sensory interference (SI – CO) and response interference (RI – SI). Like the analyses for task switching, these five dependent measures were also subject to the linear mixed-effect model analysis specified in Equation 1. For the congruent RT, the effect of Testing Time (F(2, 28.922) = 4.968, $p < .05$) and Acute Stage (F(1, 35.277) = 22.076, $p < .001$; immediately pre- vs. post-training: 733 vs. 699ms) reached significance. The post hoc tests found that the significant Testing Time effect was due to significant difference between the 1st week (741ms) and the 12th week (697ms), and 6th week (710ms) did not differ from the other two time points.

For the sensory incongruent RT, the effect of Testing Time (F(2, 27.400) = 7.562, $p < .005$) and Acute Stage (F(1, 35.508) = 11.231, $p < .005$; immediately pre- vs. post-training: 761 vs. 730ms) also reached significance. Post hoc tests found that the significant Testing Time effect was due to significant difference between the 1st week (778ms) and the 6th week (727ms), $p < .005$, and between the 1st week and the 12th week (730ms), $p < .05$

Likewise, for the response incongruent RT, the effect of Testing Time (F(2, 31.450) = 10.767, $p < .005$) and Acute Stage (F(1, 34.917) = 9.076, $p < .01$; immediately pre- vs. post-training: 766ms vs. 741ms for immediately post-exercise) reached significance, too. Post hoc tests found that the significant Testing Time effect was due to significant difference between the 1st week (792ms) and the 6th week (739ms), $p < .001$, and between the 1st week and the 12th week (728ms), $p < .001$

The only significant effect for the Sensory Interference component was Testing Time (F(2, 35.688) = 3.611, $p < .05$). Paired-wise comparisons showed that the effect was marginally stronger at 1st week (37ms) than 6th week (18ms), $p < .1$. The effect at 12th week (31ms) did not differ significantly with the other testing times though. Finally, none of the effect approached significance for the Response

Interference component.

N-back Task (updating component). The main effect of Testing Time reached significance ($F(2, 31.648) = 4.528$, $p < .05$). Post hoc tests showed that the N-back score at the 12th week (75.3%) was significantly higher than the 1st week (64.8%), and marginally different from the 6th week (68.6%). The Age covariate was significant ($F(1, 39.806) = 7.728$, $p < .05$). Age has a negative relationship with accuracy (-1.40), namely younger participants perform better than older ones.

Discussion

The goal of the current study is to examine how training intensity differentially modulates performance on subcomponents of executive functions in terms of both acute and long-term change. As already pointed out above, interactions involving the Intensity factor are informative regarding how training intensity modulates executive functions across single session of exercise or long-term training. To this end, the shifting component was more sensitive to the effect of training intensity than the inhibition and updating components, given that the only significant interaction between intensity and other factors was found for the mixing cost. Specifically, at the beginning of training program there was reduction in the mixing cost from the first to the second assessment, reflecting an acute change that was not observed at subsequent testing time, and this initial effect of acute bout exercise on the mixing cost was only apparent for the Moderate Intensity group.

A couple factors may conjointly contributed to the observed dosage and training-stage dependent effect on mixing cost. First, participants trained under the moderate intensity may initially experience higher level of arousal and alertness, which helped them better maintain two different task rules in the working memory. The moderate training intensity, however, may not be sufficient to elicit a mental state that allows one to actually carry out the switching more rapidly. This may be why only the mixing cost, but not the switch cost, showed the initial change. As the training program proceeded, because the overall processing efficiency improved, the acute change in mixing cost became less obvious, and thus the dosage-dependent effect diminished.

Moreover, this selective dosage effect may indicate that the three components of the executive function follow quite different short-term and long-term mechanisms of change. In the cognitive training literature, different components of executive function show differential practice or maintenance effect after training (Dahlin, Neely Larsson, Backman & Nyberg, 2008; Karr, Areshenkiff, Rast & Garcia-Bamera, 2014), suggesting inequivalent plasticity among components. It is likely that due to distinct brain networks involved for separate components of executive function, while some components are more prone to the impact of exercise, others are relatively robust to fitness-related change. Regarding the neural underpinnings of executive functions, there is consensus that they are the joint contribution of both a common frontoparietal network and component-specific brain regions (Wager & Smith, 2003; Wager et al., 2004). Specifically, shifting, inhibition, and updating tasks elicit overlapping activation in frontal (e.g., dorsal lateral prefrontal cortex [DLPFC]; anterior cingulate area) and parietal regions (superior and inferior parietal lobe; precuneus). Meanwhile, each of the three components also have their unique neural substrates in distinct prefrontal, occipital and temporal areas as well as subcortical regions, including caudate, thalamus, putamen, and cerebellum, for inhibition and updating (Collette, Hogge, Salmon, & ger Linden, 2006; Niendam et al., 2012). The diversity in the brain regions involved could expose each executive function to different strength of acute arousal (neurotransmitter, baseline activation … etc.) and/or long-term structural factors (BDNF, VEGF, … etc.), and hence differential patterns of behavioral trajectory accompanying exercise training.

Alternatively, the current results could reflect the differential sensitivity of the adopted tasks in detecting functional changes rather than genuine differences in the change of executive components. This is a difficult confound to rule out, because the definition of the components are basically derived from the tasks used to evaluate them. Any comparison of effect size in longitudinal changes between different constructs is prone to such challenge. Future work applying multiple tasks for each single component would help to verify whether the change (or no change) is consistent across multiple ways of measuring the function, and whether changes of different functions are comparable in magnitude after training. However, collecting multiple tasks for each component of executive function will increase the testing time, which poses practical challenges in conducting the experiment.

The mixing cost has been considered as consequence of holding competing rules simultaneously in the repeat condition, which prolongs RT comparing to the single condition where participants only need to consider one type of response rule (Rubin & Meiran, 2005). On the other hand, the switch cost requires actively shifting between rules. Since switch cost did not show any effect in the current study, it appears that exercise training did not impact the shifting component in an uniform manner. There have been studies suggesting that mixing cost and switch cost are dissociable aspects of set shifting, both in terms of developmental trajectory (Kray & Lindenberger, 2000; Mayr, 2001; Davidson et al., 2006) and brain mechanisms (Braver, Davidson, Amso, Anderson, & Diamond, 2003; Goffaux, Braver, Reynolds, & Donaldson, 2008). Given that mixing costs and switch costs may depend on distinct neural networks and/or relate to different task processing stages, it is not that surprising that exercise training modulate these two components of shifting to different extents.

The current study also found significant main effects of Testing Time and Acute Stage on components other than the mixing cost. This indicates that repeat testing across the twelve-week period induced acute and long-term effect on subcomponents of executive function, though this alone without interaction with the training intensity does not provide evidence for fitness effect. Regarding the long-term effect, the sensory interference of the inhibition component showed improvement (reduction in cost) when comparing the RT cost of the 1st and the 6th week. Similar pattern of reduction from the 1st week to the 12th week was also observed for the sensory incongruent and response incongruent RTs of the inhibition component. Likewise, the N-back performance for the updating component was the best at the 12th week as compared to the 1st and 6th week. As for the acute effect, almost all RT measures showed significant improvement between immediately before and after single bout of exercise (e.g., repeat and switch RTs for the shifting component, and congruent, sensory incongruent, as well as response incongruent RTs of the inhibition component). These results indicate that in general the participants' executive function got improved across both short and long time scale. This may be attributed to the effect of practice and learning.

In addition to the three computerized tasks, two other paper-and-pencil tests on cognitive capacity, RAPM and Digital Span, showed neither training intensity dependent improvement nor practice effect over time. It appears that these paper-and-pencil tests are less prone to repetitive administration when consecutive tests are interleaved by relatively long time period (i.e., 6 or 12 weeks in the current study). Following the same rationale, this could also be attributed to the sensitivity of the tests to the change of cognitive functions they intended to measure, or be due to the plasticity of these cognitive functions. Considering all of these results together, it seems that exercise training selectively enhances cognitive abilities. Moreover, even for subcomponents of the same cognitive construct such as the executive function, the exercise-induced plasticity is not equivalent.

To conclude, the current study provides information regarding how different components of executive function are modulated by the intensity of aerobic exercise training. The research design adopted here complemented earlier investigations on the same topic with the "with" versus "without" training designs, which poses a closer match between conditions. The results show that not all components of executive function are equally plastic, and that not all training intensities are equally effective. The current findings offer potential clue to the inconsistent reports regarding whether exercise training induces fitness effect, and promote the ideas of implementing training factors in a parametric fashion as well as dissecting the cognitive construct under investigation in a more precise and complete manner. Future research works carrying on the parametric approach like the current one and a few previous studies (Chang et al., 2011; Chang & Etnier, 2009) would be essential in integrating cognitive and exercise sciences and advancing the knowledge about optimization of exercise prescription for individual cognitive well-being.

Acknowledgements

The current work was supported by the National Science Council via grants NSC-99-2410-H008-065 and NSC-100-2628-H-008-008 to Erik Chang, and by the Ministry of Science and Technology via grants MOST-103-2911-I-009-101 (I-RICE) and MOST-103-2627-E-009-001. The authors are grateful to members of the NCU basketball and swimming teams for volunteering in the administration of the aerobic training exercise program.

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投稿日期：104 年 09 月
通過日期：104 年 12 月

Physical Education Journal
Society of Physical Education, Taipei, Taiwan
Vol. 49, No. S, pp. 75～90 (2016. 6.)

有氧運動訓練強度對中老年人執行功能之影響

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摘　要

近年來許多研究指出，以有氧運動訓練方式提升中、老年人身體活動量，可促進其認知功能。然而，這些實驗多半直接比較訓練組與對照組之差異，實驗結果僅能提供關於「有」與「無」訓練的前、後測差異。關於不同訓練參數對認知能力的影響，則只能藉由統合性分析推估。本研究目的在探討不同強度之長期有氧運動訓練，對於中、老年人三種不同的中央執行功能影響。我們在篩選後招募中、老年人共四十人，隨機分爲兩組以保留心跳率之 40% (低等強度) 及 60% (中等強度) 進行三個月的有氧飛輪訓練，並且於訓練第一週、第六週及第十二週，對兩組受試者進行三種中央執行功能成份，進行訓練前、後急性效果的測量。結果發現：中等強度訓練比低等強度訓練有效提升體適能指標 (六分鐘行走距離)；在中央執行功能的轉換 (shifting)、干擾抑制 (inhibition) 以及訊息更新 (updating) 等三種成份表現上，只有轉換能力的混合代價 (mixing cost) 指標呈現訓練強度與急性階段以及長期訓練時間點的交互作用，其餘成份皆未有此效果。有氧訓練強度差異並非一致性地影響中央執行功能的所有成份運作效能；較高強度訓練會選擇性地在作業轉換功能上展現其優勢。

關鍵詞：執行功能、有氧運動、訓練強度