The Effects of Physical Activity and Fitness on Cognitive Performance: Current Status and Future Prospects

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Abstract

Background. A growing body of literature has demonstrated that regular physical activity (PA) and high fitness levels have a positive impact on cognition. Electroencephalogram (EEG) studies, particularly those using event-related brain potentials (ERPs), have played a key role in the growth of the PA-cognition research field. This paper focuses on reviewing the relevant neuroelectric and behavioral findings on the beneficial relationship between PA and cognition across the human lifespan. The discussion focuses on whether PA reflects a general cognitive enhancement or benefits some cognitive processes more than others.

Method. An electronic literature search was conducted up to July 2018. Studies were included in this review if they provided behavioral and neuroelectric evidence within healthy people across their lifespan.

Results. Previous studies provided strong evidence of PA-linked benefits related to selective attention, cognitive control, and cognitive flexibility. Furthermore, cross-sectional studies proposed a potential improvement in working memory. Overall, reviewed studies suggested that having an active lifestyle could be associated with significant improvements in executive functions.

Conclusion. There is much evidence to support the notion that physical activity influences the neural activity of the brain and cognition. A theory to explain why an active lifestyle might benefit some cognitive processes more than others is needed. Furthermore, it is necessary to identify a set of elemental cognitive processes to understand the brain mechanisms underlying each of these processes. Optimizing the amount of PA that could maximize its benefits on brain health and function should be considered in future studies as well.

Keyword

Physical activity, Fitness, Cognitive functions, Event-Related Potentials.

認知的遂行における身体活動と身体適応の効果：研究の現状と見通し

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要旨

背景　日常的な身体活動（PA）と身体適応レベルの高さが認知にポジティブな効果を持つことを多くの研究が示している。脳波（EEG）研究，特に事象関連電位（ERP）は，PAと認知の研究分野の広がりに鍵となる役割を果たしてきた。本報告は，人間の生涯にわたるPAと認知の有益な関係を神経電気的・行動的に示す顕著な発見に焦点をあて論評する。議論では，PAが一般的な認知的向上や恩恵を特定の認知過程に与えるのかに焦点をあてる。

方法　電子媒体における文献検索が2018年７月に行われた。本報告に含む研究は，生涯健康な人々において示された行動的・神経電気的発見とした。

結果　先行研究は選択的注意，認知的制御，そして認知的柔軟性に関連したPA関連効果の有力な証拠を与えている。さらに，横断的研究は作動記憶における潜在的改善効果も示唆した。全体として，検証された研究は活動的な生活型を持つことが実行機能における有意な改善をもたらし得ることを示した。

結論　身体活動が脳の神経活動と認知に有益であることを支持する有力な証拠がある。活動的生活がなぜいくつかの認知過程においてのみ有益であるのかを説明する理論の構築が求められる。さらに，これらの基盤となる脳内メカニズムを理解するためには基本的な認知過程の同定が必要である。脳の健康と機能におけるPAの恩恵を最大にするPA量を知るために更なる研究が検討されねばならない。

キーワード

身体活動，身体適応，認知機能，事象関連電位

1. Introduction

A growing body of evidence supports that Physical Activity (PA) and exercise can confer a benefit for cognition, decrease age-related cognitive decline (Kramer & Erickson, 2007), protect against depression and mental diseases symptoms (Mrcpuk et al., 2017), and improve mood condition and sleep cycles (Loprinzi & Cardinal, 2011). These benefits arise from the crucial role of PA in decreasing insulin resistance (Way, Hackett, Baker, & Johnson, 2016), reducing inflammation (Woods, Wilund, Martin, & Kistler, 2012), increasing growth factor chemicals, improving the abundance and survival of new brain cells, and creating strong functional connectivity (Hötting & Röder, 2013; Vivar, Potter, & van Praag, 2012; M. W. Voss et al., 2013). These physiological and neurological changes are evident when comparing high-active and low-active people (Zagrebelsky & Korte, 2014; Zhao, Deng, & Gage, 2008).

Recently, people have become increasingly less active, especially in developed countries. Thus, the rate of health problems such as cardiovascular diseases, type-2 diabetes, and obesity increased (Blair, 2009). Insufficient PA is a key risk factor for death worldwide. On the global scale, one in four adults is not active enough, and more than 80% of the world's young adults are insufficiently physically active. In a comparison of the amount of physical activity between developed and developing countries, it was concluded that 26% of men and 35% of women in developed countries, and 12% of men and 24% of women in developing countries, are considered insufficiently physically active (World Health Organization, 2018). One of the most contributed factors that make people less-active is technology. However, technology makes us more efficient and productive on the other side it gives more time that we usually spend it on sedentary and passive activities. Historically, PA has demonstrated that engaging in an active lifestyle may preserve and/or enhance cognitive function not only in healthy people but also with cognitively impaired individuals (Lautenschlager et al., 2008). On the other hand, the global prevalence of insufficient PA is increasing (Moraes, Guerra, & Menezes, 2013). Therefore, it is considered to be an alarm to give more concern for the negative impacts of insufficient PA in cognition.

In PA and cognition domain, researchers have used different assessment methodologies to examine how PA influences cognitive functions. Behavioral measures are useful in cognitive function evaluation. However, Event-related brain potential (ERP) has provided additional insight into the underlying mechanisms that occur during cognitive processing, along with behavioral task performance. The high temporal resolution of the ERP technique provides information that occurs between stimulus evaluation and response execution, which deepens our understanding of how exercise influences cognition (Hillman, Pontifex, & Themanson, 2009; Luck, 2014).

ERP refers to a set of electroencephalographic activity components that occur in response to, or preparation for, a stimulus, specific sense, cognition, or motor event (Coles, Gratton, & Fabiani, 1990; Luck & Kappenman, 2011). ERP components are described by a set of positive (P) and negative (N) deflections, which are composed according to their direction and the relative time that they occur (Hruby & Marsalek, 2002). ERP components can be divided, based on their characteristics, into exogenous and endogenous components. Exogenous components are associated with the physical parameters of the eliciting stimulus (i.e., P1), while endogenous components reflect higher-order cognitive processing that often requires active participation from the subject. Examples of the most commonly measured endogenous components are P3 and contingent negative variation (CNV). P3 latency refers to the speed of information processing, while P3 amplitude reflects attentional resource allocation devoted to a given stimulus. CNV reflects the expectation of a stimulus and motor preparation (Donchin, Ritter, & McCallum, 1978; Kropotov, 2010).

ERPs can also be distinguished based on the nature of time-locking events into stimulus-locked components and response-locked components. The stimulus-locked components occur following the onset of a sensory event (i.e., P1, N1, N2, and P3) (Coles & Rugg, 1995), while response-locked components occur following the exact behavioral response such as error-related negativity (ERN), which are identified as a reinforcement learning index of error detection (Holroyd, Dien, & Coles, 1998). For further knowledge about ERP components, see Luck. (2014).

Evidence from PA-cognition research goes straight to the notion that regular PA and higher fitness levels can improve brain health and cognition, corresponding to the broad construct of cognitive functions. However, the variation of employed cognitive paradigms makes it difficult to determine which cognitive processes underlie the PA-cognition interaction. Determining the extent to which PA relates to cognitive functions will help to clarify which specific aspects of cognition could be maintained/developed by PA. This remains unreported and has important implications for the use of PA as a "treatment" to restore or enhance cognitive abilities. Moreover, finding answers to this inquiry will be essential for passing PA from the laboratory environment to more extensive clinical prescriptions. Therefore, the purpose of this paper is to answer the question of whether PA reflects a general cognitive enhancement or benefits to specific aspects of cognitive processes more than others. Additionally, this paper will assist in providing future direction for prospective studies. To achieve this aim, a body of neuropsychological research has been reviewed, including participant's characteristics, cognitive tasks, ERP components, and significant findings.

2. Methods

2.1. Search and selection strategy

Literature research was conducted, using PsycINFO, PubMed, Science Direct, and Google Scholar to gather literature. The search included papers written in English and published up to July 2018. The key terms were "physical activity", "physical fitness", "aerobic fitness", "active lifestyle" and "cognitive functions", "attention", "executive functions", "cognitive control", "cognitive flexibility", "memory" and "event-related potential", "ERP", "evoked cognitive potentials" and "neuroelectric system". The included studies had to: 1) provide objective correlates of PA/fitness on at least one cognitive function, 2) include health participants without age limitation, 3) clearly describe the PA/fitness measure that was used to classify the participants according to their PA or fitness, and 4) conduct neuroelectric and behavioral measures. Reasons for exclusion were: 1) unhealthy participants, and 2) reviews and meta-analyses.

2.2. Final selection processes

Of the 122 articles that were found after searching, 38 were excluded because they did not relate to the aim of this review. The remaining 84 articles were reviewed. Sixty-seven articles were excluded because they did not match the inclusion criteria for the following reasons: 1) did not including PA or fitness (n = 21); 2) did not assess ERPs (n = 30); 3) samples were animals (n = 3); 4) participants were not healthy (n = 7); 5) investigated concussion recovery (n = 5); 6) duplicate paper (n = 1). Therefore, seventeen studies were finally selected for further analysis. The Flowchart in Fig. 1 depicts the process of the final selection.

2.3. Data extraction

Data including age, methods of determining PA/fitness, cognitive tasks, ERP components, and significant results were extracted from the original reports. The primary outcome of interest was grouped according to different aspects of cognitive functions that were included in the final selection, as discussed below.

3. Results

By examining different cognitive functions, researchers have found that PA/fitness is linked to the efficiency of the overall cognitive construct in later ages (Chang, Huang, Chen, & Hung, 2013; Fong, Chi, Li, & Chang, 2014; Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; Hillman, Kramer, Belopolsky, & Smith, 2006; Hillman, Weiss, Hagberg, & Hatfield, 2002; Pontifex, Hillman, & Polich, 2009; Winneke et al., 2012). Other studies have also shown positive

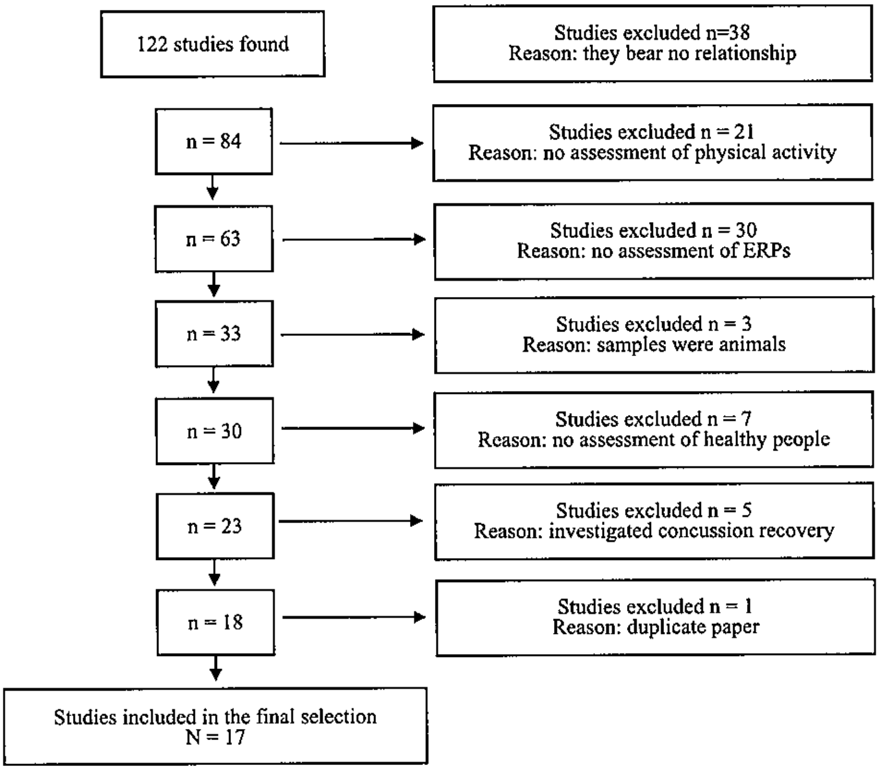

Figure 1. Flowchart of articles through the search and study selection

Table 1. *Overview of the Studies Included the behavioral and neuroelectric evidence from PA-cognition research*

Task	Study	Participants (n, age ± SD)	Measure of PA	ERP components	Results	
					Behavioral	Neuroelectric
STIMULUS DISCRIMINATION						
Simple RT, Choice RT	(Cirillo et al., 2017)	11 more-active (21.6±0.9y) 11 less-active (21.6±0.5y)	IPAQ	CNV	Longer RT in less-active	No difference
Visual oddball task and Three-stimulus discrimination task	(Pontifex et al., 2009)	10 high-fit elderly (66.2 ± 3.5y) 13 low-fit elderly (67.4 ± 3.2 y) 9 high-fit adults lower fit (20±1.5y) 12 higher-fit adults (20.3±1.1y)	VO2max	P3a, P3b	Higher-fit performed shorter RT	Increased P3b amplitude in high-fit younger subjects No difference in P3a amplitude between older subjects
Visual oddball task	(Hillman et al., 2005)	12 high-fit children (9.1 ±1.2y) 12 low-fit children (9.6 ±0.6y) 15 high-fit adults (19.1±1.2y) 12 low-fit adults (19.5 ±1.5y)	FT	P3	Higher-fit performed shorter RT	Increased P3 amplitude in higher-fit compared to lower-fit Decreased P3 latency in higher-fit compared to lower-fit Decreased P3 latency in adults compared to children
	(McDowell et al., 2003)	21 high-active adults, 16 low-active adults (22.7 ± 3.7y) 18 high-active elderly, 18 low-active elderly (67.7±3.7y)	VO2max	P3	NT	Increased P3 latency in older groups No differences in P3 between the elder high active group and young groups Increased P3 amplitude in the younger high-active than the younger low-active

Table 1. *Continued*

Task	Study	Participants (n, age ± SD)	Measure of PA	ERP components	Results	
					Behavioral	Neuroelectric
S1-S2-S3 paradigm	(Hillman et al., 2002)	12 fit elderly (63.5 ± 2.8y) 12 sedentary elderly (65.0 ± 2.7y) 12 sedentary adults (23.3 ± 3.3y)	YPAS VO2max	P3, CNV	NSD	Decreased P3 latency in the fit elderly Decreased CNV amplitude in fit elderly
INHIBITORY CONTROL						
Flanker task	(Winneke et al., 2012)	11 high-active adults (43.1±3.2y) 9 low-active adults (38.9±3.8y) 11 high-active elderly (58.8±3.4y) 13 low-active elderly (57.6±2.3 y)	BAQ	N2, P3	More-active performed smaller interference cost	Increased N2 amplitude in the high-active adults No difference in P3 between high and low active
	(Pontifex et al., 2011)	24 high-fit children (10.0±0.6y) Lower-fit children (10.1 ± 0.6 y)	VO2max PAR-Q	P3, ERN	Higher-fit performed more accurately	Increased P3 amplitude in higher-fit Decreased P3 latency in higher-fit Decreased ERN amplitude in higher-fit
	(Hillman, Buck, et al., 2009)	19 high-fit children (9.3±0.9y) 19 low-fit children (9.5±1.0y)	FT	P3, ERN	Higher-fit performed more accurately	Increased P3 amplitude in higher-fit Decreased ERN amplitude in higher-fit
	(Themanson et al., 2008)	72 younger adults (19.7 ±1.6y)	VO2max	ERN	NSD	Increased ERN amplitude in the higher-fit
	(Hillman et al., 2004)	8 high-active elderly (65.9 ± 8.1y) 8 moderate-active elderly (65.6 ± 6.3y) 8 low-active elderly (68.8 ± 5.3y) 8 adults (20.4 ±1.9y)	YPAS	P3	NT	Increased P3 amplitude in moderate and high active older groups compared to younger group in the incompatible trials. Increased P3 amplitude in low active older group compared to the younger group in the neutral condition. Decreased P3 latency in younger group compared to the low and moderate active older groups
EXECUTIVE CONTROL						
Task switching	(Fong et al., 2014)	16 endurance exercisers (68.37 ± 3.68y) 16 Tai Chi trainees (67.31 ± 4.92 y) 16 sedentary elderly (68.93 ± 4.28y) 16 young adults (22.43 ± 2.58y)	IPAQ	P3	Less-active performed longer RT	Increased P3 amplitude in all groups relative to sedentary older group No difference in P3 amplitude between young adults and endurance exercisers and Tai Chi trainees
	(Kamijo & Takeda, 2010)	20 active adults (20.4±0.3y) 20 sedentary adults (22.3±0.4y)	IPAQ	P3	More-active performed smaller switching cost RT	Decreased P3 amplitudes in the active subjects relative to the sedentary subjects
	(Scisco et al., 2008)	26 high-fit adults, 26 low-fit adults (19.62 ±1.63y)	IPAQ VO2MAX	P3a, P3b	NSD	No differences in ERPs between high-fit and low-fit
	(Themanson et al., 2006)	32 high and low physically active older (60–71y), 34 younger adults (18–21y)	YPAS	ERN	More-active performed smaller global switching cost RT	Decreased ERN amplitude in physically active older adults compared to less physically active
	(Hillman et al., 2006)	17 active elderly (63.7±0.9y) 15 sedentary elderly (65.9 ±0.8) 18 active adults (19.4±0.3 y) 19 sedentary adults (19.4±0.8y)	YPAS	P3	More-active performed shorter RT	Increased P3 amplitudes in the active groups Decreased P3 latencies in the active groups on difficult trials

Table 1. *Continued*

Task	Study	Participants (n, age ± SD)	Measure of PA	ERP components	Results	
					Behavioral	Neuroelectric
WORKING MEMORY A modified Sternberg task	(Chang et al., 2013)	20 high-active elderly (67.90±2.38y) 20 low-active elderly (67.85±2.13 y)	IPAQ	N1, P3	More-active performed shorter RT	Decreased P3 latency in the high active group Increased N1 and P3 amplitudes the high active group
	(Kamijo et al., 2010)	22 high-fit adults (19.95 ± 1.9y) 22 low-fit adults (20.4 ±2.2y)	VO2max	CNV	NSD	Increased CNV amplitude in the lower-fit group during the speed instructions

Note. y= year; IPAQ = international physical activity questionnaire; BAQ = Baecke activity questionnaire; YPAS = Yale physical activity survey for older adults; PAR-Q = physical Activity Readiness Questionnaire; FT = field test; VO2max = maximal oxygen uptake mL/kg/min; CNV = contingent negative variation; ERN = error related negativity; NSD = not significant difference; NT = not reported.

links between PA/fitness among children (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Pontifex et al., 2011). In addition, this positive relationship was also observed with adults (Cirillo, Finch, & Anson, 2017; Kamijo, O'leary, Pontifex, Themanson, & Hillman, 2010; Kamijo & Takeda, 2010; McDowell, Kerick, Santa Maria, & Hatfield, 2003; Scisco, Leynes, & Kang, 2008; Themanson, Hillman, & Curtin, 2006; Themanson, Pontifex, & Hillman, 2008). In the next section, we review the neurobehavioral evidence to date from PA-cognition research (see table 1).

3.1. Stimulus discrimination

Discrimination task (oddball paradigm) is one of the first tasks that provided evidence about the association between PA/fitness and a healthy brain, which was revealed through behavioral and neuroelectric indices of cognitive performance. The oddball task requires participants to respond to infrequent target stimuli surrounded by a train of non-target stimuli. It is considered that the oddball paradigm requires relatively minimal cognitive control compared to other tasks (i.e., go/nogo, flanker, and Stroop) (Hillman, Kamijo, & Pontifex, 2012). A majority of PA-cognition interaction studies have indicated that a higher level of PA or aerobic fitness is associated with larger P3 amplitude and/or shorter P3 latency during stimulus discrimination tasks.

Hillman et al. (2005) examine the relationship between aerobic fitness and cognitive function by comparing both high and low-fit preadolescent children and younger adults during the visual oddball task. The study indicated that high-fit children had greater P3 amplitude compared to low-fit children, and high-fit younger adults had shorter P3 latency compared to low-fit younger adults. This study also showed high-fit children had a faster reaction time than low-fit children. These findings suggest that fitness is associated with cognitive processing speed and has implications for increasing cognitive health.

Pontifex et al. (2009) investigated the influence of fitness on the neuroelectric correlates of attentional processing and orienting during a simple and three-stimulus oddball task among younger and older subjects. In the oddball task, higher-fit individuals yielded shorter RT and larger P3b amplitude compared to their lower-fit age-matched counterparts. In the three-stimulus oddball task, larger P3b amplitude was only found in higher-fit younger adults. The study suggests that fitness-related differences in cognitive aging may be specific to attentional processing under low perceptual discrimination difficulty tasks. The study also indicates that, under conditions of the three-stimulus oddball task, aerobic fitness only affected attentional processing in younger adults. Importantly, fitness did not modulate the P3a component. P3a relates to attention directed towards a distracting stimulus among targeted and non-targeted stimuli. The lack of modulation could be interpreted as attentional orienting processes being unaffected by fitness. Thus, fitness appears to selectively affect the attentional system rather than a more generalized cognitive enhancement.

McDowell et al. (2003) examined the task performance and P3 component during an oddball task among older participants who were classified into high and low-active groups. The study showed that low-active elderly participants expressed a larger area under the curve than those observed in the high-active group, suggesting that higher levels of PA in the elderly are associated with neural efficiency in response to lower-order cognitive processes. Hillman et al. (2002) investigated the influence of cardiovascular fitness on cognitive and motor processes among older and younger aerobically trained and sedentary adults by participating in an S1-S2-S3 paradigm. In this task, a warning stimulus (S1), such as the word "Easy" or "Hard" was shown to give the participants information about the difficulty level of an upcoming decision task (S2). On the presentation of S2, participants had to decide which was the taller bar (7.68 cm difference and 0.03 cm difference for the easy and hard conditions, respectively). Participants were instructed to decide which bar is taller (left or right) without giving a response. A box was presented (S3) and participants were asked to press the corresponding box of the taller bar as quickly as possible. Results revealed that lower-fit individuals had larger CNV relative to their higher-fit counterparts, whereas no difference was observed for RT to S3, suggesting that fitness level is associated with greater economy of motor preparation for both younger and older participants. Interestingly, older sedentary individuals showed the longest P3 latency to S2, followed by the older fit and both younger groups, which suggests that physical fitness is associated with slower cognitive decline in older individuals.

Getzmann et al. (2013) examined whether long-term physical activity is associated with lower susceptibility to distraction. Auditory discrimination task was performed among physically active and inactive elders in which the participant hears three tones (500 Hz, 100Hz or 200Hz). Eighty Percent of the trials were frequent standard stimuli (1000 Hz), and 20% were rare deviant stimuli (either 500 Hz or 2000 Hz, each 10%). The duration of the tones was short (200 ms) and long (400 ms). Participants were instructed to discriminate the duration of the tones by pressing one response button for short tones and another button for long tones. The results indicated that the inactive group showed longer RT with the deviant tones than the active group. This was accompanied by a stronger frontal positivity (P3a) and increased activation of the anterior cingulate cortex, suggesting a stronger involuntary shift of attention towards task-irrelevant stimulus features in inactive compared to active seniors. These results indicate a positive relationship between physical fitness and attentional control in the elderly.

To reinforce the idea that a higher level of PA or fitness is associated with superior cognitive performance, Cirillo, Finch, & Anson (2017) measured changes in behavior and brain activity during preparation and performance of simple and choice reaction time tasks among less and more physically active young adults. The study found that, although CNV did not modulate between the study groups, reaction and premotor times were larger for both tasks in less active relative to the more active participants. The results suggested that decreased levels of PA in young adults may have a negative impact on cognitive processing and motor preparation. Collectively, the previous studies showed that higher PA and greater aerobic fitness are associated with faster cognitive processing across the human lifespan.

3.2. Inhibitory control

Several ERP studies have performed modifications of the Eriksen flanker task (Eriksen & Eriksen, 1974) to investigate the relationship between PA/fitness and inhibitory aspects of cognitive control. In a typical Flanker task, participants are required to respond to a centrally presented target stimulus while ignoring distracting stimuli appearing in the periphery. The flanker task consists of two main trial types: congruent trials (e.g., > > > > > or < < < < <), in which the target stimulus is flanked by consistent distractors, and incongruent trials (e.g., < < > < < or > > < > >), in which the target stimulus is flanked by inconsistent distractors. Flanker task requires not only selective attention to the target stimulus, but it also needs more efforts to avoid the distractor effect, resulting in longer reaction times and/or more errors in incongruent-relative to congruent-trials (Machado, Wyatt, Devine, & Knight, 2007). The difference in the reaction time between congruent and Incongruent Condition refers to Flanker effect, in which smaller flanker effects reflect more efficient executive control (Kopp, Rist, & Mattler, 1996).

Researchs that utilized versions of the flanker showed that PA/fitness is associated with improvement in executive control. A recent study by Winneke et al. (2012) investigated the association between PA and attentional control in a group of middle-aged (ages 30:45 years) participants. Results indicated that highly active younger middle-aged exhibited lower interference costs (RT differences between incongruent and congruent) and larger N2 amplitude compared to low active middle-aged participants, suggesting that PA bears potential to benefit attentional control.

Hillman et al. (2004) compared between low, moderate, and high physically older adults and younger control groups on neutral and incomputable conditions. The study showed that high and moderate active older adults exhibited larger P3 amplitude compared to younger adults for the incompatible condition, and low-active older adults exhibited smaller P3 amplitude relative to younger adults. Further, the longest P3 latency was for low-active older adults, followed by moderate active, highly active, and younger adults respectively. These results suggest that a higher amount of PA reflects positively on executive control function in older adults by affecting the distribution of P3 amplitude, which has been related to attentional processes, and by decreasing P3 latency, which relates to the speed of cognitive processing.

In Pontifex et al. (2011) study, 48 preadolescent children were separated into higher and lower-fit groups. The study found that lower-fit exhibited lower-response accuracy comparing with the higher fit group. Larger P3 amplitude, shorter latency, and greater modulation of P3 amplitude between the congruent and incongruent conditions were also observed with the high-fit group relative to the low-fit group. Interestingly, higher-fit participants exhibited smaller ERN amplitudes in the congruent condition, and greater modulation of the ERN between congruent and incongruent condition, suggesting that lower-fit children may have more difficulty than higher-fit in the flexible modulation of cognitive control processes to meet task demands. Consistent with the previous results, Hillman et al. (2009) investigated the relationship between aerobic fitness and executive control among higher- and lower-fit children. The study showed that lower-fit children performed less accurately relative to lower-fit children. ERP data indicated that P3 amplitude was smaller for lower- compared to higher-fit children, and lower-fit children exhibited larger ERN amplitude and smaller error positivity amplitude compared to higher-fit children. The study suggested that physical fitness is associated with better cognitive performance on an executive control task, resulting in the greater allocation of attentional resources during stimulus encoding and a subsequent reduction in conflict during response selection.

Furthermore, Themanson et al. (2008) investigated the relationships between fitness and ERN amplitude, post-error accuracy, and post-error RT, in conjunction with task instructions emphasizing either speed or accuracy among young adults. Although the study showed that RT and accuracy did not modulate with respect to fitness level in either instruction conditions, ERN amplitude was larger in high-fit compared with low-fit participants under accuracy conditions. The study suggested that higher fitness levels may be related to increased flexibility in the modulation of cognitive control to meet specific task demands and correct behavior, especially when participants were instructed to respond as accurately as possible. To summarize, studies in older adults indicate that regular PA improves older adults' performance on tasks that rely on more inhibitory control (e.g., incongruent condition) (Hillman et al., 2004; Winneke et al., 2012). Studies in young adults and children provided limited support for PA-related benefits in selective attention and inhibitory control, with the bulk of the supportive evidence relating to accuracy rates and indices of post-error behavior (Hillman, Buck, et al., 2009; Pontifex et al., 2011; Themanson et al., 2008). Taken together, the majority of the studies that performed the flanker paradigm to examine the relation of PA to cognitive control have observed a positive relation across the lifespan.

3.3. Executive control

Task switching paradigm generally involves the ability to shift attention from one task to another. In other words, the participant during the task selects and switches between multiple task sets. For instance, the participant might be instructed to respond to a digit displayed in two colors, in which green digit means determining whether the digit is greater or less than 5, while the red digit means determining whether the digit is an even or odd number. In case two trials presented with the same response rule respectively this is considered to be a non-switch trial, while if the response rule was changed this is considered to be a switch trial. The RT difference between non-switch trials and switch trials is referred to switching cost. Smaller switching cost reflects more efficiency in cognitive flexibility (Banich, 2009; Monsell, 2003).

Studies conducted with older adults showed that response times were shorter for active participants relative to sedentary and ERP data supported shorter P3 latency (Hillman et al., 2006), and larger amplitude in active participants (Fong et al., 2014; Hillman et al., 2006). New Program with younger adults, although Sisco et al. (2008) reported that behavioral and neuroelectric data among young adults did not modulate between high-fit and low fit participants, Kamijo and Takeda (2010) found that smaller switching cost on RTs and P3 amplitudes for the active group relative to the sedentary group, and Themanson et al. (2006) supported a positive relationship between PA and ERN.

Taken together, it seems that elderly people can benefit from the active lifestyle in terms of task-switching performance and electrocortical processes of executive control. However, with young adults, there is an inconsistent result of that argument. In addition, it could be noticed that no study was conducted among children which obscures our understanding of whether it could be an improvement in shifting cost throughout childhood.

3.4. Working memory

Working memory task generally requires holding information (e.g., digits, letters) for a brief amount of time and rapidly updating the given information to respond correctly (Sternberg, 1966). In addition to the body of research described above, two studies have utilized a modified version of Sternberg's working memory task. Change et al. (2013) investigated the effects of PA on working memory among elderly people. The study showed that response times were faster for the high-active relative to the low-active participants. Neuroelectric measures also indicated that P3 latency decreased, and N1 and P3 amplitudes increased in high-active comparing to low-active participants, suggesting that regular PA is associated with increasing the efficiency of evaluating the stimulus during the retrieval phase as well as engaging more attentional resources for the early discriminative processes during the encoding phase of a working memory task. Kamijo et al. (2010) examined the relationship between aerobic fitness and task preparation within young adults under speed and accuracy instructions. Although the study did not report a difference between higher-fit and lower-fit participants on the behavioral level, CNV amplitude was significantly larger for lower-fit compared to higher-fit participants during speed condition. The results from Kamijo et al. study support that lower-fit individuals may rely to a greater extent on cognitive control processes to respond under speeded conditions, whereas higher-fit individuals may maintain a more constant level of control in both task instructions. Overall, the results from the Change et al. and Kamijo et al. studies suggest higher amounts of PA during daily activities and a high fitness level can facilitate working memory by allocating more attentional resources among older adults and maintaining an efficient motor preparation in younger adults.

3.5. Current status and Future prospects

Figure 2 illustrates the cognitive processes that have been examined in the previous PA-cognition studies. It is clear that PA interacts with the electrical potential of the brain during performing of a variety of cognitive tasks (Figure 2). Regardless of the participant's age and cognitive task, PA releases cognitive resources to increase the engagement of task-relevant neuroelectric activation, resulting in superior cognitive performance. PA and

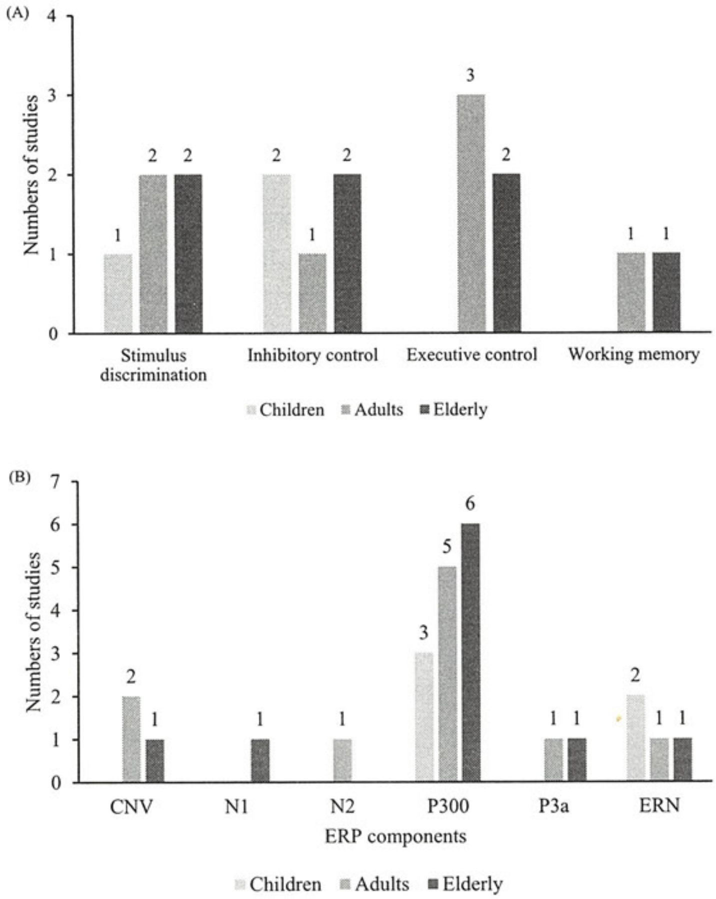

Figure 2. Numbers of studies per associated cognitive functions (A) and ERP components (B) that investigated the interaction between PA or fitness and cognition using the ERP technique at different ages.

neuroelectric system interactions are often associated with more efficient performance during the task demands. The present study characterizes the current state of what we know about the PA-cognition interaction across the human lifespan.

Literature indicated that behavioral and neuroelectric concomitants underlying different cognitive processes are influenced by PA or aerobic fitness. On the other hand, some other findings were inconsistent with the previous results, which limited the generalization of the beneficial relationship between PA and cognition or directed the influence of PA toward a specific cognitive process for a specific age. For instance, the study of Scisco et al. (2008) reported that the relationship between fitness and executive control could be observed only in later ages. This comes from the fact that cognitive abilities become less efficient as we age because of the slow deterioration of the prefrontal cortex (Raz, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). If so, it is possible that physical fitness could improve cognitive abilities in later ages by slowing down the cognitive decline (Hillman et al., 2004; 2006) and increasing neurogenesis in the prefrontal cortex (Colcombe et al., 2003).

Further, Hillman et al. (2009) reported

insignificant RT differences between high and low fit children. This result may be due to greater demand for executive control during the Eriksen task, or the cognitive enhancement could not be observed with earlier ages. The differences between study samples, with respect to their age and PA level, may explain why P3 amplitude was not modulated by PA level in the study of Winneke et al. (2012).

Cirillo et al. (2017) could also not report any brain electrical oscillations changes between more active and less active adults. Most of the previous studies recruited higher-active/fit and lower-active/fit. The difference in the amount of PA between the two groups in Cirillo et al. study could be the reason for not observing any modulation on ERPs data. This could lead to another argument regarding the sufficient amount of PA that could reflect cognitive enhancement.

Pontifex et al. (2009) showed that P3b component modulated by the degree of fitness while P3a did not. These results in the PA-induced improvement in cognition could be exclusive for some cognitive processes rather than a general enhancement. So far, there is strong scientific support for the idea that the relationship between PA and cognition is bidirectional, and that PA and exercise have direct effects on the brain, similar to how it directly affects specific muscles (M. Voss, 2015). Furthermore, the inconsistent behavioral result in Hillman et al. (2002) study was expected due to the fixed time between the target stimulus (S2) and the response cue (S3), which allows the subjects to anticipate the response cue.

The studies of Pontifex et al. (2011) and Hillman et al. (2009) showed that ERN amplitude decreases in higher-fit relative to the lower-fit participants, while Themanson et al. (2008) reported a decreasing in the ERN amplitude. This conflicting finding may be because the participants in Pontifex et al. study were instructed to respond as quickly and accurately as possible and in Hillman et al. study to respond as quickly as possible, while in Themanson et al. study participants were instructed to respond as accurately as possible. Therefore, the different task instructions could be the reason behind this conflict.

In prospective studies, it will be needed to focus on a set of cognitive processes such as attention orientation, interference control, and motor preparation to examine whether PA can influence these processes, or PA-cognition interaction is directed toward specific cognitive processes. Previous studies that targeted elderly people showed better cognitive performance with high-active/fit relative to less active/fit under different tasks that examined stimulus discrimination, inhibition, cognitive flexibility, and working memory (Chang et al., 2013; Fong et al., 2014; Hillman et al., 2004; Hillman et al., 2006; Hillman et al., 2002; Pontifex et al., 2009; Winneke et al., 2012). As this body of literature continues to grow, prospective studies need to examine whether PA-linked cognitive benefits are applied whereby the specific type of activity/exercise or just a general involving in an active lifestyle. In younger adults, previous work indicated that higher physically active and aerobically fit individuals exhibit faster RT in oddball paradigm and smaller switching cost in task switching paradigm (Cirillo et al., 2017; Kamijo et al., 2010; Kamijo & Takeda, 2010; McDowell et al., 2003; Scisco et al., 2008; Themanson et al., 2006; Themanson et al., 2008). Further studies will be needed to examine other cognitive processes such as inhibitory control and working memory. Due to the lack of studies that targeted children, the PA-linked cognitive benefits are still ambiguous; however, evidence supports the idea that PA could influence cognitive performance associated with cognitive processing speed and inhibitory control (Hillman, Buck, et al., 2009; Hillman et al., 2005; Pontifex et al., 2011). Thus, future research targeting especially executive control and working memory may provide a better understanding of whether the PA-cognition benefits could have been achieved in younger ages or it is exclusive with later ages.

The evaluation of cognitive changes is conceptually different according to the targeted aspects of cognition in the research area of PA and cognitive enhancements. Chang, Liu, et al. (2012) categorized cognitive assessments as examining attention, cognitive control, information processing, intelligence and achievements tests, memory, and motor speed and learning. As the previous studies investigated various aspect of cognitive process, future studies should target unexplored cognitive aspects.

Although the neural mechanisms underlying the relationship between PA and some aspects of cognition are known, little is understood about the consequences of stop being physically active on cognitive functions. Furthermore, it is necessary to characterize the type and dose of PA to consider the mechanistic background for why alterations in such characteristics might differentially induce changes in cognition. Such insights might contribute toward a greater understanding of how to maximize the characteristics of PA and exercise to acquire the greatest cognitive improvements.

Further, it is important to mention that although the majority of cross-sectional studies showed a positive relation between PA and cognition, some studies have failed to replicate this result. The failure might have occurred because of many moderators' factors could impact on PA-cognition relationship. Understanding which factors have the most effect will help us to be more aware of how moderators' factors can contribute to the relationship between PA and cognition. Some possibilities that merit further studies are distinguishing the differences of the psychophysiological indices of aerobic and anaerobic exercise, participants' ages, and genetic factors.

4. Conclusions

In this review, we examined the behavioral and neuroelectric evidence for the relationship between PA/fitness and some aspects of cognition in a healthy population. In older adults, cross-sectional data indicate that PA predicts superior performance under discrimination, inhibition, cognitive flexibility, and working memory task demands. However, further investigations are needed to determine whether this relationship reflects involvement in a specific type of activity. In younger adults, evidence indicated that higher PA/fitness levels are associated with faster information processing, better cognitive flexibility, and more efficient preparatory activity. In children, there is a difficulty to determine the specific aspect of cognition that PA may affect due to the lack of studies. However, some evidence indicated that regular PA influences cognitive processing and cognitive control. More investigations are required in school-aged children (ages 6-11 years) to determine whether the influence of PA and fitness relates specifically to cognitive aspects such as task switching and cognitive flexibility. Although the evidence to date supports a wide range of executive functions benefiting from regular PA, other aspects of cognitive processes need to be examined, such as attentional orienting processes P3a (observed on three discrimination task), early mismatch detector N200 (observed on no-go trials in go/nogo task), and interference processing N400 (observed on Stroop task) to fully characterize the benefits that could be achieved by PA with healthy populations. Future directions also need to give more attention to the critical question of what kind of activites responsible for inducing cognitive changes. It is apparent that being involved in an active lifestyle has favorable consequences for cognitive functions across the human lifespan, particularly in the context societies becomes less active. Hopefully, the previous and new findings will motivate more people to stay aerobically active, and for policymakers to give more attention to promoting this culture, especially in developing countries.

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