Review Article

Effects of acute exercise on executive function in children with and without neurodevelopmental disorders

Keishi Soga¹, Keita Kamijo² and Hiroaki Masaki²*

¹ Graduate School of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan
² Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan

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Abstract An increasing number of studies have examined the effects of acute aerobic exercise on executive function (i.e., higher-order cognitive abilities involved in goal-directed behaviors) in healthy children. More recently, studies have begun to extend these empirical findings to children with neurodevelopmental disorders such as attention-deficit/hyperactivity disorder (ADHD) and autism spectrum disorder (ASD). Here, we review what is known about the effects of acute exercise on executive function in children with and without neurodevelopmental disorders. Overall, moderate acute aerobic exercise can transiently improve executive function in children with and without neurodevelopmental disorders. Further, these effects of acute exercise may differ depending on type of exercise, participant characteristics (e.g., fitness levels, executive function capacity, type of neurodevelopmental disorder), and timing of cognitive task administration (i.e., after versus during exercise). Despite the increasing number of findings, it is still premature to suggest effective exercise types and/or intensity levels to produce improvements in executive function in children. Further studies are needed to address this issue. Finally, future research directions are discussed in more detail.

Keywords: acute exercise, executive function, children, neurodevelopmental disorders

Introduction

It is well known that exercise is important for physical and mental health, such as the prevention of cardiovascular diseases and depression in both children and adults. However, there is growing concern that children in developed countries are becoming increasingly sedentary. Several recent longitudinal randomized controlled intervention studies have indicated that regular physical exercise improves cognitive function during childhood, suggesting that physical exercise also plays an important role in cognitive development and brain health. Along this line of thought, higher physical activity levels or aerobic fitness are associated with superior academic achievement. These findings highlight the importance of regular physical exercise during childhood.

Researchers have also examined the effects of physical exercise on cognitive function from a different perspective, namely, the effects of a single bout of acute exercise. In general, these studies have found that young adult participants improved cognitive performance after 20-30 min of moderate acute aerobic exercise (for a review, see Chang et al., 2012, Lambourne et al., 2010, Tomporowski, 2003, and Verburgh et al., 2013). If indeed acute exercise has such beneficial effects, these research findings might have an important role to play in exercise promotion. However, it is noteworthy that the effects of acute exercise on cognitive function seem to differ depending on cognitive task administration timing. In a study by Pontifex et al. (2007), college students performed a cognitive task during aerobic exercise. Results demonstrated that cognitive performance declined during exercise compared to a non-exercise control condition, which is inconsistent with previously observed post-acute exercise effects. Thus, we believe that the effects of acute exercise should be considered separately based on whether cognitive tasks are conducted after or during exercise.

Although earlier studies examined the effects of acute exercise on cognitive function in young adults, newer studies have investigated these effects in children. More recently, such findings have been extended to children with neurodevelopmental disorders, such as attention-deficit/hyperactivity disorder (ADHD) and autism spectrum disorder (ASD). To our knowledge, no comprehensive review article has focused on both children with and without neurodevelopmental disorders, although a few reviews have separately considered the effects of acute exercise on cognition in healthy children or in children with neurodevelopmental disorders. In this review, we will update earlier reviews of healthy children, and then address findings in children with neurodevelopmental dis-
orders.

Studies reviewed herein have focused on higher-order cognitive functions, referred to as executive function (or cognitive control). It has been well documented that neurodevelopmental disorders are linked to executive dysfunction\(^3\). Thus, before turning to the review, we begin by providing a definition of executive function and summarizing what is known about the relationship between neurodevelopmental disorders and executive dysfunction. We then separately review findings concerning the effects of acute exercise on cognition based on the timing of cognitive task administration (i.e., post- or during-task exercise).

Executive function

Executive function is responsible for the ability to orchestrate thought and plan a schedule in accordance with an internal goal, and includes three core abilities: inhibitory control, working memory, and cognitive flexibility\(^26,27\). Inhibitory control is required to correctly respond in the face of distracting irrelevant stimuli in accordance with planned actions\(^25\), or to stop an ongoing response\(^29\). Working memory is the ability to temporarily hold and manipulate information mentally in an accessible state for ongoing processing\(^29\). Cognitive flexibility is involved in flexibly dealing with changing situations or in adjusting incorrect action in a more appropriate direction\(^26\). These components of executive function continue to develop from childhood to young adulthood\(^31\). Executive function is primarily supported by a network of brain regions involving the prefrontal cortex\(^32,33\), networks that exhibit protracted developmental time courses\(^30\). Additionally, it has been well documented that executive function is implicated in academic achievement\(^35-37\), indicating an association between superior executive functioning and better academic performance.

Neurodevelopmental disorders and executive function

According to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5: American Psychiatric Association, 2013)\(^39\), neurodevelopmental disorders are characterized as impairments in social skills, personal independence, and intellectual faculties that occur during childhood development. Based on symptom characteristics, neurodevelopmental disorders are categorized into intellectual disabilities, communication disorders, ADHD, ASD, specific learning disorders, motor disorders, and other disorders that cannot be classified by specific symptoms. In the US, ADHD diagnosis has been rapidly increasing, in that parent-reported ADHD now describes approximately 10% of the child/youth population aged 4-17 years, a rate increase of 21.8% during 2003-2007\(^39\). In Japan, the number of children diagnosed with neurodevelopmental disorders (e.g., ADHD, ASD and learning disability) has significantly increased over the past decade (Ministry of Education, Culture, Sports, Science and Technology of Japan, 2014)\(^40\).

In addition to specific impairments emphasized in diagnostic criteria (e.g., social interaction, intelligence, and attention), executive dysfunction is a hallmark of neurodevelopmental disorders\(^31\). Children with ADHD or ASD exhibit inferior inhibitory control compared to healthy control children\(^42,43\). A developmental cross-sectional study indicated that children with ADHD exhibit delayed development of executive function compared to typically developing children\(^44\). Furthermore, relative to typically developed children, children with ADHD, ASD, and dyslexia have abnormal brain structure\(^45-47\), and exhibit differential brain activation during the resting state\(^48\), as well as during executive function tasks\(^49-51\). Because accumulating evidence has indicated positive effects of acute exercise on executive function, it becomes interesting to clarify how acute exercise influences executive function in children with neurodevelopmental disorders, who exhibit clear patterns of executive dysfunction.

Effects of acute exercise on executive function in healthy children

Post effects of acute exercise on executive function.

Table 1 summarizes previous findings about the effects of acute exercise on executive function in healthy children. Hillman et al. (2009)\(^52\) provided the first support for the notion that acute aerobic exercise has beneficial effects on executive function in preadolescents (mean age = 9.6 years). They employed a within-participants design that permitted control of individual differences. Participants performed a modified flanker task after 20 min of walking on a treadmill (exercise intensity: 60% maximal heart rate [HRmax]) and after 20 min of seated rest. Condition order was counterbalanced across participants. The flanker task, which consists of congruent (i.e., <<<<<< or >>>>>>) and incongruent trials (i.e., >><> or <<<<), has been widely used to assess inhibitory control\(^53\). This task requires participants to respond to the centrally presented target direction and ignore the task-irrelevant stimuli (i.e., flankers). That is, the incongruent trials require greater amounts of inhibitory control to respond to the target stimulus, due to the requirement of inhibiting incorrect response activation caused by the task-irrelevant stimuli. Children exhibited greater response accuracy for incongruent trials after exercise compared with the rest condition, whereas no such difference was observed for the congruent trials. Considering greater inhibitory demands in the incongruent trials, it is plausible that inhibitory control is selectively improved after acute aerobic exercise. In addition to behavioral measures (i.e., response accuracy and reaction times; RT), this study also assessed changes in the P3 ERP component after acute aerobic exercise. The amplitude of this component is believed to
Table 1. Summary of previous findings about effects of acute exercise on executive function in healthy children

<table>
<thead>
<tr>
<th>Authors</th>
<th>N</th>
<th>Age (years)</th>
<th>Participant characteristics</th>
<th>Exercise</th>
<th>Cognitive task</th>
<th>Timing of cognitive task</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hillman et al. (2009)</td>
<td>20</td>
<td>mean age = 9.6</td>
<td>Healthy</td>
<td>20 min of walking (60% HRmax)</td>
<td>flanker</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Chen et al. (2014)</td>
<td>83</td>
<td>third-and fifth grade school children (age range = approximately 9-11)</td>
<td>Healthy</td>
<td>30 min of jogging (60-70% HRmax)</td>
<td>flanker task, n-back task, and switch task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Budde et al. (2008)</td>
<td>99</td>
<td>age range = 13-16</td>
<td>Healthy</td>
<td>10 min of coordinative exercise (mean HR = approximately 120 bpm)</td>
<td>d2 test</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Best (2011)</td>
<td>33</td>
<td>age range = 6-10</td>
<td>Healthy</td>
<td>20 min of exergame (70-80% HRmax)</td>
<td>flanker task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Hogan et al. (2013)</td>
<td>30</td>
<td>mean age = 14.2</td>
<td>Healthy (lower-fit and higher-fit)</td>
<td>20 min of cycling (60% HRmax)</td>
<td>hybrid flanker-Go/NoGo task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Drollette et al. (2014)</td>
<td>40</td>
<td>age range = 8-10</td>
<td>Healthy (lower-performer and higher-performer)</td>
<td>20 min of walking (60-70% HRmax)</td>
<td>flanker task</td>
<td>after</td>
<td>Improvement in lower performer</td>
</tr>
<tr>
<td>Budde et al. (2010)</td>
<td>59</td>
<td>age range = 15-16</td>
<td>Healthy (lower-performer and higher-performer)</td>
<td>12 min of running (50-85% HRmax)</td>
<td>digit span task</td>
<td>after</td>
<td>Improvement in lower performer</td>
</tr>
<tr>
<td>Drollette et al. (2012)</td>
<td>36</td>
<td>age range = 9-11</td>
<td>Healthy</td>
<td>20 min of walking (60% HRmax)</td>
<td>flanker task and n-back task</td>
<td>during</td>
<td>No change</td>
</tr>
<tr>
<td>Soga et al. (2015)</td>
<td>55</td>
<td>age range = 15-16</td>
<td>Healthy</td>
<td>13 min of walking (60-70% HRmax)</td>
<td>flanker task and n-back task</td>
<td>during</td>
<td>No change in inhibitory control, and Impairment for working memory</td>
</tr>
</tbody>
</table>

Notes: HR = heart rate, bpm = beats per minutes
reflect attentional resources allocated toward a stimulus. The P3 amplitude increased after exercise compared to the rest condition, suggesting that the observed improvements in response accuracy after acute aerobic exercise might be due to exercise-induced enhancement of attentional resources.

Chen et al. (2014) examined the effects of acute aerobic exercise on each key aspect of executive function (i.e., inhibition, working memory, and cognitive flexibility) in third- and fifth-grade school children. This study employed a between-participants design, in which participants were assigned to either an exercise group or a rest group. Participants in the exercise group performed three executive function tasks before and after 30 min of moderate-intensity jogging (60-70% HRmax), whereas participants in the rest group performed the same tasks before and after 30 min of seated rest. The exercise group exhibited shorter RTs for all three executive function tasks relative to the rest group at post-test, with no group differences at pre-test. These findings suggest that 30 min of moderate intensity exercise has beneficial effects on all key aspects of executive function. Thus, it is likely that a single bout of 20-30 min of moderate-intensity exercise can improve executive function in children, which is consistent with evidence for young adults.

**Different types of acute exercise.** Although the majority of previous acute exercise studies focused on aerobic exercise, some studies have tried to elucidate whether the effects differ based on type of exercise. Budde et al. (2008) investigated the effects of coordinative exercise on inhibitory control in adolescents (age range = 13-16 years), using the d2 test to assess attention. This task consisted of the letters “b” and “p” with one or two dashes arranged above or below the letter, and required participants to detect the letter “d” with two dashes within a string of the other letters. On the first day, participants performed the d2 test after a regular school lesson (pre-test). One week later, they were assigned to either a coordinative exercise group (duration = 10 min, mean HR = 122.3 beats per min [bpm]) or a normal sport lesson group (duration = 10 min, mean HR = 122.0 bpm). The coordinative exercise included five different exercises selected from coordinative training forms (e.g., bouncing a basketball), whereas the normal sport lesson did not include any specific coordinative requests. Both groups performed the d2 test immediately after the exercise treatment (post-test). Although both exercise groups showed improved d2 post-test performance relative to pre-test, the coordinative exercise group demonstrated greater improvements compared to the normal sport lesson group. These results imply that coordinative exercise can improve attention more effectively, compared to more conventional forms of exercise.

Best (2011) investigated how cognitive engagement influences the effects of acute exercise on executive function. Participants (age range = 6-10 years) underwent four conditions: a) low physical activity and low cognitive engagement (e.g., watching a video while seated), b) low physical activity and high cognitive engagement (e.g., seated video gaming), c) high physical activity (70-80% HRmax) and low cognitive engagement (e.g., jogging exergaming), and d) high activity and high cognitive engagement (e.g., challenging and interactive exergaming). After approximately 20 min of each activity, participants performed a modified flanker task. Using a within-participants design, each condition was conducted on separate days in a counterbalanced order. They evaluated the interference effect (i.e., RT difference between incongruent and congruent trials) based on an assumption that less interference reflects superior inhibitory control. Results indicated that smaller interference effects were observed in both exergame conditions relative to the seated conditions, suggesting that acute exercise can improve inhibitory control irrespective of cognitive demands during exercise, and that acute cognitive engagement does not affect executive functioning.

**Characteristics of participants.** Hogan et al. (2013) investigated the effects of acute aerobic exercise on executive function in lower-fit and higher-fit adolescents (mean age = 14.2 years). Participants performed a hybrid flanker-Go/NoGo task after 20 min of aerobic exercise (60% HRmax) and 20 min of seated rest, on separate days in a counterbalanced order. This task consisted of eight letter arrays (congruent: BBBBB, DDDDD, UUUUU, and VVVVV; incongruent: DDBDD, BBDBB, VVUVV, and UUUVU). Participants responded to the centrally presented “B” and “U” letters (Go condition), and had to withhold their responses to centrally presented “D” and “V” letters (NoGo condition). Higher-fit participants exhibited shorter RTs after exercise compared to after the rest condition, whereas no such improvement was observed in their lower-fit counterparts. Additionally, lower-fit participants exhibited higher error rates for NoGo relative to Go trials in the rest condition, whereas error rate did not differ between trial types in the exercise condition. Higher-fit participants exhibited greater error rates for the NoGo relative to Go trials across conditions. Although the beneficial effects of acute aerobic exercise for each group were differentially observed for each task performance measure (i.e., RTs for higher-fit, errors rate for lower-fit), these findings suggest that acute aerobic exercise can transiently improve inhibitory control irrespective of participants’ fitness levels. We further speculate that acute exercise might have improved cognitive inhibition (i.e., interference control) and response inhibition (i.e., NoGo) for higher-fit and lower-fit individuals, respectively.

Drollette et al. (2014) investigated the effect of acute aerobic exercise on executive function using a modified flanker task, in which participants (age range = 8-10 years) were divided into two groups based on their per-
formance on incongruent trials during a rest condition: lower- and higher-performers. Participants performed the flanker task after 20 min of moderate intensity exercise (60-70% HRmax) and seated rest on separate days. Task performance did not differ between conditions for higher-performers, whereas lower-performers exhibited greater response accuracy for both congruent and incongruent trials after exercise compared to the rest condition. Additionally, lower-performers showed increased P3 amplitude in the exercise condition relative to the rest condition, whereas no such increase was found for higher-performers. These findings suggest that the effects of acute aerobic exercise might differ based on participants’ baseline inhibitory control capacity.

Budde et al. (2010) also examined whether the effects of acute aerobic exercise on executive function differ based on participants’ baseline performance levels. Participants (age range = 15-16 years) were divided into three groups: a low intensity exercise group (50-60% HRmax), a moderate intensity exercise group (70-85% HRmax), and a non-exercise control group. The participants were further classified into lower- and higher-performers based on their pre-test performance. Participants underwent a digit span task before and after 12 min of aerobic exercise or seated rest. The digit span task is a measure of working memory, in which participants are given numbers and letters (e.g., a8k5) and are asked to report the numbers in ascending order, followed by the letters in alphabetical order (i.e., s5ak). Lower-performers in the low intensity exercise group improved their performance, whereas other participants (i.e., higher-performers in the low intensity, moderate intensity, and control groups) did not show such improvements, replicating the above described ERP study. It is likely that the beneficial effects of acute exercise are greater for individuals who have lower levels of executive function.

Effects of in-task acute exercise on executive function.

Drollette et al. (2012) examined the effects of acute aerobic exercise on inhibitory control and working memory in preadolescents (age range = 9-11 years) using a within-participants counterbalanced design. Participants underwent modified flanker and modified spatial n-back tasks before, during, and after moderate intensity aerobic exercise (60% HRmax) or seated rest. The spatial n-back task asked participants to press one of two buttons corresponding to whether the stimulus appeared in the same location as n trials before. This task has been used to assess working memory, as it requires memorization and manipulation of information. Participants’ performance improved after moderate intensity aerobic exercise relative to the rest condition for the flanker task, replicating previous findings; whereas no such improvement was observed for the n-back task. Although it is unclear why n-back performance did not change after exercise, this pattern suggests that the effects of exercise may differ based on the aspect of executive function tested (i.e., inhibition or working memory). Additionally, participants showed comparable task performance before and during exercise for both the flanker task and n-back task. This finding contradicts a prior adult study, which indicated that young adult participants exhibited inferior flanker task performance during exercise. Thus, it is likely that the effects of in-task aerobic exercise on executive function differ depending on participant age.

Soga et al. (2015) support this assertion, in which the effects of in-task aerobic exercise were examined in adolescent children (age range = 15-16 years) using the same procedure as Drollette et al. (2012). Specifically, they found that flanker performance was maintained during moderate intensity exercise (60-70% HRmax), which is consistent with the findings for preadolescent children, whereas n-back performance declined during exercise compared with the rest condition. Given that little evidence exists examining the effects of in-task exercise on executive function, future studies are needed to elucidate whether in-task exercise differentially influences executive function depending on age. Collectively, we should emphasize again here that the effects of acute exercise should be considered separately, depending on whether cognitive tasks are conducted after or during exercise.

Effects of acute exercise on executive function in children with neurodevelopmental disorders

As mentioned above, it is likely that the beneficial effects of acute exercise on executive function is disproportionately greater for children who have lower levels of executive function. According to these findings, children with neurodevelopmental disorders, who typically exhibit executive dysfunction, should be sensitive to the beneficial effects of acute exercise. Several recent studies have extended the findings of the effects of acute exercise in healthy children to children with neurodevelopmental disorders. In this section, we review the effects of acute exercise on executive function in children with ADHD, ASD, and intellectual disability. No study, to our knowledge, has investigated the effects of in-task exercise on executive function in children with neurodevelopmental disorders; such that this section focuses on the after-effects of acute exercise. Table 2 summarizes previous findings about the effects of acute exercise on executive function in children with neurodevelopmental disorders.

Attention Deficit Hyperactivity Disorder (ADHD).

Chang et al. (2012) investigated the effects of 30 min of moderate intensity aerobic exercise on executive function in children with ADHD (age range = 8-13 years). This study employed a between-participants design, in which participants were assigned to exercise and non-exercise control groups. Participants in the exercise group performed a Stroop task before and after 30 min of treadmill running.
<table>
<thead>
<tr>
<th>Authors</th>
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<th>Cognitive task</th>
<th>Timing of cognitive task</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chang et al. (2012) 66)</td>
<td>40</td>
<td>age range = 8-13</td>
<td>ADHD</td>
<td>30 min of running (50-70% of HR reservation)</td>
<td>Stroop task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Piepmeier et al. (2015) 67)</td>
<td>32</td>
<td>mean age = 10.8</td>
<td>ADHD and Healthy</td>
<td>30 min of cycling (mean HR = 147.7 bpm)</td>
<td>Stroop task, Tower of London, and Trail Making Test</td>
<td>after</td>
<td>Improvement for inhibitory control</td>
</tr>
<tr>
<td>Pontifex et al. (2013) 68)</td>
<td>40</td>
<td>age range = 8-10</td>
<td>ADHD and Healthy</td>
<td>20 min of aerobic exercise (no description of exercise mode) (65-75% HRmax)</td>
<td>flanker task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Chuang et al. (2015) 69)</td>
<td>19</td>
<td>age range = 8-12</td>
<td>ADHD</td>
<td>30 min of running (60% of HR reservation)</td>
<td>Go/NoGo task</td>
<td>after</td>
<td>Improvement</td>
</tr>
<tr>
<td>Anderson-Hanley et al. (2011)</td>
<td>22</td>
<td>age range = 8-21</td>
<td>ASD</td>
<td>20 min of exergaming (no description of exercise intensity)</td>
<td>Stroop task, digit span task, and Color Trials test</td>
<td>after</td>
<td>Improvement for working memory</td>
</tr>
<tr>
<td>Vogt et al. (2013) 70)</td>
<td>11</td>
<td>mean age = 16.0</td>
<td>IDD</td>
<td>10 min of Cycling (mean HR after exercise = 143.0 bpm)</td>
<td>simple RT task</td>
<td>after</td>
<td>Improvement</td>
</tr>
</tbody>
</table>

Notes: HR = heart rate, bpm = beats per minutes, ADHD = attention-deficit/hyperactivity disorder, ASD = autism spectrum disorder, IDD = intellectual and developmental disabilities, RT = reaction time
at 50-70% of HR reservation (mean HR during exercise = 150.1 bpm), whereas the non-exercise control participants performed the same task before and after 30 min of seated rest. The Stroop task asked participants to state ink colors, which were mismatched to the words (e.g., BLUE printed in red ink), while also inhibiting the prepotent response to read the word. This task has been widely used to assess inhibitory aspects of executive function. The time required to name the colors of 50 words was measured. Although both groups exhibited shorter RTs (reaction times) at post- relative to pre-test, the time difference between pre- and post-test was greater for the exercise group compared to the non-exercise control group. The observed shorter time duration at post-test in the control group could be due to practice or learning effects. Thus, these findings suggest that acute aerobic exercise can improve inhibitory control (i.e., executive function) in children with ADHD.

Pipmeier et al. (2015)67 replicated this finding. Children with and without ADHD (mean age = 10.8 years) performed the Stroop task after 30 min of moderate intensity aerobic exercise (mean HR during exercise = 147.7 bpm) and 30 min of seated rest. Stroop task performance was better for the exercise relative to the rest condition across the ADHD and non-ADHD groups, suggesting that aerobic exercise improved inhibitory control irrespective of ADHD diagnosis. Note that this study also assessed other aspects of executive function (cognitive flexibility, planning and problem solving) and found that acute aerobic exercise did not affect these aspects of task performance. As is the case for healthy children63, it is likely that the effects of acute exercise on executive function differ depending on the cognitive task being undertaken. Stated differently, acute aerobic exercise may have a disproportionately greater effect on inhibitory control relative to other aspects of executive function, and these disproportionate effects may be similar for children with and without ADHD.

Two ERP studies support the beneficial effects of acute exercise on inhibitory control in children with ADHD. In Pontifex et al. (2013)68, ADHD children and healthy children (age range = 8-10 years) performed a modified flanker task after 20 min of moderate intensity aerobic exercise and 20 min of seated rest in a counterbalanced order. Both ADHD and healthy control groups exhibited greater response accuracy and stimulus related processing, which was assessed via the P3 ERP component, for the exercise relative to the rest condition. Additionally, these researchers assessed academic performance using the Wide Range Achievement Test, 3rd Edition, and indicated that both ADHD and healthy control children exhibited better performance on tests of reading comprehension and arithmetic after aerobic exercise relative to after seated rest. Given that executive function has been closely associated with academic achievement35-37, such beneficial effects on academic performance are perhaps not surprising.

Chuang et al. (2015)69 also examined the effects of acute aerobic exercise on inhibitory control in ADHD children (age range = 8-12 years). Participants performed a Go/NoGo task after 30 min of moderate intensity aerobic exercise and after 30 min of seated rest. ADHD participants had shorter RTs and evidenced more efficient response preparation, which was reflected by a negative slow wave cortical potential (i.e., contingent negative variation: CNV). The CNV is thought to reflect anticipation-related cognitive process and response preparation for a stimulus70,71. Collectively, these ERP findings suggest that acute aerobic exercise can improve inhibitory control for both ADHD and healthy children, supporting the above described behavioral findings.

**Autism spectrum disorder (ASD).** Anderson-Hanley et al. (2011)72 used a within-participants design to investigate the effect of acute aerobic exergaming on executive function in ASD. Participants (age range = 8-21 years) performed three executive function tasks that assessed inhibition, working memory, and cognitive flexibility, before and after 20 min of exergaming and 20 min of seated rest. Working memory performance improved after exergaming compared with the after seated rest condition, whereas no such improvement was observed for performance on inhibition and cognitive flexibility tasks. These findings indicate that the beneficial effects of acute exercise are specific to working memory in children with ASD, which is inconsistent with the ADHD studies67. Such selective effects might make sense, given that ASD behavioral symptoms such as repetitive behavior are associated with deficits in working memory73. Thus, although it is speculated that the effects of acute exercise on executive function differs between ADHD and ASD children, further studies are required due to limited data for children with ASD.

**Intellectual and developmental disorders (IDD).** Vogt et al. (2013)70 investigated the effects of moderate intensity cycling (mean HR after exercise = 143.1 bpm) on cognitive function in children (mean age = 16.0 years) with intellectual and developmental disabilities (IDD). Participants performed a simple RT task before and after 10-min of cycling exercise and 10-min seated rest, in a counterbalanced order. This task required participants to touch a stimulus (yellow light), which was presented on the center of a touchscreen with a random inter-stimulus interval. RTs decreased after compared to before exercise, whereas no such change was observed for the rest condition, suggesting that acute aerobic exercise can improve cognitive function in IDD children. Unlike the above-described studies focusing on ADHD66-69 and ASD71, Vogt et al. (2013)70 used a simple cognitive task which requires minimal executive function. Although it may be difficult to use executive function tasks for IDD children,
further evidence is required to elucidate whether the effects of acute exercise on cognition differ depending on type of neurodevelopmental disorder.

**Future directions**

In the past decade, a growing number of empirical studies have examined the effects of acute exercise on executive function in children. However, there still exist some important open questions, which need to be addressed in future studies. First, it remains unclear what type and intensity of acute exercise is most beneficial for enhancing executive function in children. The majority of research showed that simple aerobic exercise such as running and cycling has beneficial effects on executive function in children; and some other studies have found positive effects of aerobic exercise requiring motor skills. These studies mainly employed moderate intensity exercise. We believe that the public is quite interested in this open question. Therefore, further research should try to demonstrate the most effective exercise type and intensity for improvements in executive function.

From the findings of Drollette et al. (2012) and Soga et al. (2015), it is reasonable to suggest that the effects of acute aerobic exercise on executive function differ based on the timing of cognitive task administration (i.e., after exercise or during exercise). However, additional studies are needed to investigate the time course effects of acute exercise on executive function, since to our knowledge no study has examined how long the beneficial effects of acute exercise actually last in children. We speculate that time course effects vary as a function of exercise type, intensity, and/or duration.

Evidence of the effects of acute exercise in children with ADHD has been accumulating, whereas only two studies focused on other neurodevelopmental disorders (i.e., ASD: Anderson-Hanley et al. (2011); IDD: Vogt et al. (2013)). Although the existing evidence suggests that aerobic exercise can improve executive function in children with neurodevelopmental disorders, this effect may differ depending on type of neurodevelopmental disorder. Therefore, it is worthwhile exploring the effects of exercise in other neurodevelopmental disorders (e.g., Communication Disorders and Specific Learning Disorder).

Possible underlying mechanisms for improvements in cognitive function have been proposed for adults. For example, it has been suggested that changes in arousal levels and/or cerebral blood flow during and after acute exercise can influence cognitive function. Further, recent research highlighted that exercise-induced lactate is associated with enhancement of brain function. However, these suggestions remain inconclusive, and no study has examined such mechanisms in children. Shedding light on such mechanisms could inform the issue as to which exercise types and durations are most effective.

**Conclusion**

Accumulating evidence has suggested that all key aspects of executive function (i.e., inhibition, working memory, and cognitive flexibility) in healthy children can be improved after moderate aerobic exercise. These findings are consistent with recent research suggesting that acute aerobic exercise can improve academic performance, which is closely associated with executive function. Although newer studies have shown the post-acute exercise effects may differ depending on type of exercise and participant characteristics (i.e., fitness levels, executive function capacity), these are still controversial issues due to relatively scarce empirical data. Lastly, it seems in line with adult studies that the effects of acute exercise on cognition differ based on the timing of cognitive task administration (i.e., post- versus in-task exercise).

Studies focusing on children with neurodevelopmental disorders showed beneficial effects of acute aerobic exercise on cognitive function, which are in line with the findings for healthy children. Specifically, it is likely that acute aerobic exercise has beneficial effects on inhibitory control in children with ADHD, and on working memory in children with ASD. The general effects of acute exercise on cognition in children with IDD have been also confirmed. However, given that there is still a paucity of empirical evidence in children with neurodevelopmental disorders, it is premature to conclude whether acute exercise has the same beneficial effects on cognition across children with and without neurodevelopmental disorders. We hope that these findings can be used to help motivate children both with and without neurodevelopmental disorders to undertake physical exercise.

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this article.

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