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ATTENTION-DEFICIT/HYPERACTIVITY DISORDER

Aerobic Fitness and Inhibition in Young Children: Moderating Roles of ADHD Status and Age

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We examined the relation between aerobic fitness and inhibition in young children with and without attention deficit hyperactivity disorder (ADHD)-risk status. Participants (91 ADHD risk, 107 typically developing, $M_{\text{age}} = 6.83$, 53.5% male, 68.2% Caucasian) completed an assessment of aerobic fitness and a flanker task requiring variable amounts of inhibitory control. Aerobic fitness was positively associated with inhibition. When inhibitory control demands were largest, the relation varied as a function of ADHD-risk status such that the link between aerobic fitness and inhibition was significant only for children with ADHD risk. The relation between aerobic fitness, status, and inhibition was further moderated by age for interference control. Specifically, the positive relation between aerobic fitness and interference control was only significant for younger children with ADHD risk. A fitness–cognition link appears in young childhood that seems particularly salient for those in the earliest school years with ADHD risk. The findings extend work on typically developing children and suggest that exploring aerobic fitness interventions to address executive function impairments in children at risk for ADHD is warranted.

Attention deficit hyperactivity disorder (ADHD) is a highly prevalent neurobiological disorder, characterized by developmentally inappropriate presentations of inattention and/or hyperactivity/impulsivity (American Psychiatric Association, 2000, 2013). Individuals with ADHD typically experience significant impairment in multiple domains (American Psychiatric Association, 2000, 2013), including poor academic achievement (Frazier, Youngstrom, Glutting, & Watkins, 2007), grade retention (Loe & Feldman, 2007), and social maladjustment (Hoza, 2007). In addition to these impairments, a large proportion of children with ADHD exhibit one or more executive function deficits (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005). Children possessing both ADHD and executive function deficits exhibit greater impairment and poorer outcomes than children

with ADHD alone (Biederman et al., 2004). Therefore, understanding factors that may mitigate executive function deficits in children at risk for ADHD is important. Research conducted with typically developing (TD) children shows a positive association between aerobic fitness and executive function (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009); however, there is a dearth of research investigating this association in children with elevated symptoms of ADHD.

Inhibition deficits are reliably observed in children with elevated ADHD symptoms (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Inhibition is a component of executive function involving the capacity to suppress a dominant response (i.e., response suppression) and ignore competing information (i.e., interference control) in order to engage in an appropriate manner (Mullane, Corkum, Klein, & McLaughlin, 2009). When compared to TD peers, children with ADHD consistently demonstrate poorer performance on computerized tasks of inhibition, including decreased

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reponse accuracy (Rubia, Smith, & Taylor, 2007; Wiersma, van der Meere, Roeyers, Van Coster, & Baeyens, 2006; Wodka et al., 2007) and poorer interference control (Mullane et al., 2009). These impairments in inhibition are associated with increased hyperactive and inattentive behavior (Pliszka, Borcharding, Spratley, Leon, & Irick, 1997), poorer emotion regulation (Walcott & Landau, 2004), and academic difficulties (Biederman et al., 2004).

Researchers have observed a positive association between aerobic fitness and inhibitory aspects of executive functioning (Hillman, Erickson, & Kramer, 2008). *Aerobic fitness* is the ability to sustain aerobic physical activities and describes the physiological limit to the rate at which an individual can deliver and consume oxygen (Rowland, 1996). In TD 8- to 11-year-old children, higher aerobic fitness is associated with better inhibition, including less variability in reaction time on an inhibitory control task (Wu et al., 2011). Moreover, in another TD sample ($M_{\text{age}} = 9.4$), higher fit children had superior allocation of attentional resources and better interference control in comparison to lower fit counterparts (Hillman et al., 2009). To date, little research has investigated the extent to which aerobic fitness may be beneficial for children with elevated ADHD symptoms.

Among the few studies examining this possible connection, Smith et al. (2013) implemented an 8-week, 26 min/day moderate-to-vigorous physical activity intervention with young children (grades K-3) at risk for ADHD and participants significantly improved on an inhibition task. It is interesting that other work has shown children 8–10 years of age with ADHD improve in inhibition performance even after a single bout of physical activity (Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). Because physical activity positively contributes to aerobic fitness levels (Rowlands, Eston, & Ingledew, 1999), these findings suggest that children with ADHD who are more aerobically fit may exhibit better inhibition than those who are less aerobically fit. Moreover, researchers have posited that children with executive function-related deficits may benefit more from executive function interventions than TD peers (Diamond & Lee, 2011). Thus, the relation between aerobic fitness and inhibition may be stronger for children with elevated ADHD symptoms because they are more likely to experience executive function deficits as compared to their TD peers. The present study examines this hypothesis.

Most work examining the relation between aerobic fitness and inhibition has targeted middle childhood and beyond (Hillman et al., 2009; Pontifex et al., 2013; Wu et al., 2011). However, it may be especially important to examine these relations during earlier phases of development when there is greater neuroplasticity (Mannuzza et al., 2008). Accordingly, the aim of this investigation was to examine the relation between aerobic fitness and inhibition in a sample of young children with and without risk of developing ADHD. Based on extant literature, we hypothesized that aerobic fitness would positively associate with

inhibition performance and that this association would be stronger for children at risk for ADHD than TD children. We expected age to further moderate this association, such that aerobic fitness would be more beneficial at younger ages, especially when at risk for ADHD.

METHOD

Participants

Data were taken from the baseline assessment of a larger physical activity intervention study on children with and without ADHD risk (see Hoza et al., 2014). Young children were recruited from participating schools within two small, suburban U.S. cities. Four participants in the larger study were missing data required for the present work, leaving 198 children (91 ADHD risk, 107 TD) for the present analyses who ranged in age from 4 to 8 years ($M_{\text{age}} = 6.83$, $SD_{\text{age}} = .97$). The sample was 53.5% male, was racially and ethnically diverse (68.2% Caucasian, 14.1% mixed race, 8.1% African American, 2.0% Asian, and 7.6% other races), and came from homes with at least one parent possessing some postsecondary education (74.0%).

Eligibility and status assignments were determined through a two-step screening. First, parents and teachers completed the ADHD-IV Rating Scale, a normed measure of *Diagnostic and Statistical Manual of Mental Disorders* (American Psychiatric Association, 2000) ADHD symptoms (DuPaul, Power, Anastopoulos, & Reid, 1998). Second, parents completed the ADHD module of the National Institute of Mental Health Diagnostic Interview Schedule for Children, Version IV (DISC-IV; Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000), an interviewer-administered structured clinical interview that assesses child psychiatric diagnoses. In addition, parents and teachers completed the Impairment Rating Scale, a measure of child impairment across multiple domains (Fabiano et al., 2006).

ADHD-risk participants. Participants at or above the 90th percentile on the Hyperactive/Impulsive or Total subscales of the ADHD-IV Rating Scales by parent or teacher report were eligible for secondary screening as a participant with ADHD risk. To qualify as ADHD risk, at the secondary screening participants had to exhibit the following attributes:

- 1a. Five or more symptoms of hyperactivity/impulsivity by parent report on the DISC-IV.
- 1b. If participants failed to meet five endorsed symptoms by parent report on the DISC-IV, similar to the methods used in the Multimodal Treatment Study of Children with ADHD (Hinshaw et al., 1997), up to two unique hyperactive/impulsive symptoms by

teacher report on the ADHD-IV Rating Scale could be used to attain the required symptom count.

2. Impairment in two or more domains by parent and/or teacher report on the Impairment Rating Scale or by parent report on the DISC-IV.

Our emphasis on hyperactivity/impulsivity and selection of a subdiagnostic threshold of five symptoms was based on our focus on young children and developmental considerations in diagnosing ADHD (see Barkley, 2003).

Typically developing participants. Participants below the 90th percentile on the Hyperactive/Impulsive, Inattentive, and Total subscales of the ADHD-IV Rating Scales by parent and teacher reports were eligible for secondary screening as TD participants. To qualify as TD, at the secondary screening participants had to exhibit four or fewer symptoms of hyperactivity/impulsivity and inattention by parent report on the DISC-IV.

Exclusion criteria were (a) standardized scores less than 78 (i.e., 1.5 *SD* below the mean) on nonverbal, verbal, and total IQ assessments from the Kaufman Brief Intelligence Test, Second Edition (Kaufman & Kaufman, 2004); (b) parent report of diagnosis of a pervasive developmental disorder, current seizure disorder, or intellectual disability; (c) taking medication for attentional or behavioral problems (which could impact cognitive assessment performance); (d) inability to participate in physical activity; (e) residing with current caretaker less than 6 months; and (f) no English-speaking caretaker with telephone access.

Considering all sources of symptom reporting, the mean numbers of unique symptoms endorsed were significantly higher ($ps < .001$) for the ADHD-risk group (hyperactivity/impulsivity symptoms, 8.5 [$SD = 0.8$]; inattentive symptoms, 8.3 [$SD = 1.3$]) than those for the TD group (hyperactivity/impulsivity symptoms, 2.4 [$SD = 2.1$]; inattentive symptoms, 2.3 [$SD = 2.4$]).

Measures

Child Attentional Network Task. The Child Attentional Network Task (ANT; Rueda et al., 2004) is an individually administered computerized task that assesses inhibition. Participants respond to the direction of a centrally located target fish that is presented either individually or amid an array of distractor fish on each side. Participants indicate the direction of the target fish by pressing one of two buttons on a response pad corresponding to left or right. The task consists of congruent (target fish in the same direction of distractor fish), incongruent (target fish in the opposite direction of the distractor fish), and neutral (target fish presented individually) trials. A 24-trial practice block was completed, followed by six blocks of 48 trials. Equal numbers of congruent, incongruent, and neutral trials

appeared randomly within each block. The target and distractor fish were 3 cm tall and were presented for 1,700 ms followed by an interstimulus interval of 450 ms. Congruent and incongruent response accuracy, as well as interference control (congruent response accuracy – incongruent response accuracy), were evaluated. The incongruent trials, relative to the congruent and neutral trials, result in perceptually induced interference necessitating concurrent activation of both the correct response (elicited by the target fish) and the incorrect response (elicited by the distractor fish) before stimulus evaluation is complete. Thus, incongruent trials require greater amounts of response inhibition to execute the correct response (Spencer & Coles, 1999). The subtraction of incongruent response accuracy from congruent response accuracy isolates the interference control component of inhibition (Mullane et al., 2009). Because individuals do not realistically benefit from increased task interference, negative interference scores (where incongruent response accuracy is greater than congruent response accuracy) were set to equal zero. Forns et al. (2014) supported the validity and objectivity of the ANT with children.

Progressive Aerobic Cardiovascular Endurance Run. The 15-m version of the Progressive Aerobic Cardiovascular Endurance Run (PACER; McClain, Welk, Ihmels, & Schaben, 2006) was administered in groups to assess aerobic capacity. Participants run back and forth at a specified pace (8.5 km/hr, quickening by 0.5 km each minute) across a 15-m area with lines at each end. A trial is completed when participants run from one end line to the other before the sound of a pace-keeping beep. When participants reach the line, they wait for the beep prior to running the next trial in the opposite direction. Each minute is designated by the sound of a triple beep to cue that the pace will quicken. When a participant fails to reach the end line by the beep, that trial is considered a miss. The trial number prior to the second miss (consecutive or nonconsecutive) is used as the final score. PACER scores demonstrate good reliability and validity in children and adolescents (Plowman & Meredith, 2013).

Procedures

Within participating schools, all families with children in grades K-2 were invited to participate. A letter and consent documents, along with the ADHD-IV rating scale, were sent home and returned by interested families. For consenting families, teachers completed the school version of the ADHD-IV about their child, and a baseline screening session was scheduled if initial inclusion criteria were met. Families were compensated \$50 for completing the secondary screening. During this session, which included collection of demographic information, the computerized ANT was administered individually to children by research assistants masked to ADHD-risk status. On a different day, to

control for acute physical activity effects on inhibition, the PACER was administered in groups.

Data Analysis Strategy

Hierarchical multiple regression analyses were used to examine study hypotheses. Aerobic fitness, ADHD-risk status (i.e., ADHD risk or TD), and participant age were entered in the first step of the model predicting inhibition. In the second step of the model, three two-way interactions were entered. Finally, to determine whether the relation between aerobic fitness, ADHD-risk status, and inhibition further varied as a function of age, a three-way interaction term (Fitness × Status × Age) was entered in the final step of the model. Following the method outlined by Aiken and West (1991), all continuous predictors in the model were mean-centered at entry into the model and ADHD-risk status was weight effect coded (ADHD risk = $-.54$, TD = $.46$). When the hypothesized three-way interaction was not significant, a simplified model was examined including only the main effects and the hypothesized two-way Fitness × Status interaction. Significant interactions were decomposed following procedures outlined by Aiken and West (1991) and for the continuous moderator (i.e., participant age) simple slopes were computed at low (-1 SD) and high ($+1$

SD) levels. The Dawson and Richter (2006) online utility was used to plot simple slopes and conduct slope differences tests for three-way interactions.

RESULTS

Preliminary Analyses

Means, standard deviations, and intercorrelations among study variables are presented in Table 1. As expected, both higher levels of aerobic fitness and being older were associated with better inhibition (i.e., higher levels of congruent and incongruent response accuracy and lower levels of interference control). Bivariate associations among ADHD-risk status and the response accuracy measures indicated TD participants were more accurate in their responses than ADHD-risk participants (congruent response accuracy, $p = .01$; incongruent response accuracy, $p = .01$). Unexpectedly, ADHD-risk status was not significantly correlated with interference control ($p = .13$).

Hierarchical Regression Analyses

Results for the initial models are presented in Table 2. For congruent response accuracy, the three-way interaction

TABLE 1
Means, Standard Deviations, and Pearson's Correlations Among Study Variables

Variable	1	2	3	4	5	6	M	SD	Range
1. Aerobic Fitness	–						12.12	4.39	2.00–32.00
2. ADHD-Risk Status (ADHD risk = 0; TD = 1)	.15*	–					0.54	0.50	0.00–1.00
3. Participant Age	.26***	–.01	–				6.83	0.97	4.44–8.90
4. Congruent Response Accuracy	.32***	.18*	.39***	–			87.59	12.40	35.42–100.00
5. Incongruent Response Accuracy	.31***	.19**	.45***	.77***	–		78.06	19.06	14.58–100.00
6. Interference Control	–.17*	–.11	–.34***	–.23**	–.79***	–	10.16	11.67	0.00–66.67

Note: ADHD = attention deficit hyperactivity disorder; TD = typically developing.
* $p < .05$. ** $p < .01$. *** $p < .001$.

TABLE 2
Initial Models Examining the Three-Way Interaction of Aerobic Fitness, ADHD-Risk Status, and Age Predicting Inhibition

Step	Variable	Outcome								
		Congruent Response Accuracy			Incongruent Response Accuracy			Interference Control		
		b	t	ΔR^2	b	t	ΔR^2	b	t	ΔR^2
1	Aerobic Fitness	.60	3.21**	.23	.80	2.86**	.27	–.19	–1.04	.14
	ADHD-Risk Status	3.84	2.43*		6.23	2.63**		–2.35	–1.49	
	Age	4.35	5.19***		8.03	6.41***		–3.93	–4.70***	
2	Fitness × Status	–.08	–.21	.02	–1.15	–1.93	.03	.98	2.46*	.03
	Fitness × Age	–.48	–2.21*		–.48	–1.46		.02	.07	
	Status × Age	–.47	–.27		–.70	–.28		–.05	–.03	
3	Fitness × Status × Age	–.55	–1.26	.01	.51	.77	.00	–.96	–2.21*	.02

Note: *bs* are unstandardized coefficients at the predictor's entry into the equation. ADHD = attention deficit hyperactivity disorder.
* $p < .05$. ** $p < .01$. *** $p < .001$.

between aerobic fitness, ADHD-risk status, and age was not significant ($p = .21$). Moreover, the simplified model examining if the association between aerobic fitness and congruent response accuracy varied as a function of ADHD-risk status did not yield a significant two-way interaction ($b = -.34, p = .37$).

The three-way interaction predicting incongruent response accuracy was not significant ($p = .44$; see Table 2). However, the simplified model showed the association of aerobic fitness with incongruent response accuracy to vary by ADHD-risk status ($b = -1.41, p = .01, \Delta R^2 = .02$). Simple slope analyses indicated that for ADHD-risk participants, better aerobic fitness associated with better inhibition (i.e., higher incongruent response accuracy scores, $p < .001$), whereas this association was not significant for TD participants ($p = .44$; see Figure 1).

For interference control, the three-way interaction between aerobic fitness, ADHD-risk status, and age was significant (see Table 2). Simple slope analyses indicated that the association between aerobic fitness and interference control was significant only for younger, ADHD-risk status participants ($p = .002$), such that better aerobic fitness associated with better inhibition (i.e., lower scores on the interference control measure; see Figure 2). The magnitude of this association was significantly different from the same nonsignificant associations for younger, $t(190) = 3.28, p = .001$, and older, $t(190) = 2.32, p = .02$, TD participants but not significantly different from the nonsignificant association for older ADHD-risk participants, $t(190) = 1.64, p = .10$. In addition, the difference between the slopes for the younger and older TD participants was not significant, $t(190) = -1.49, p = .14$.

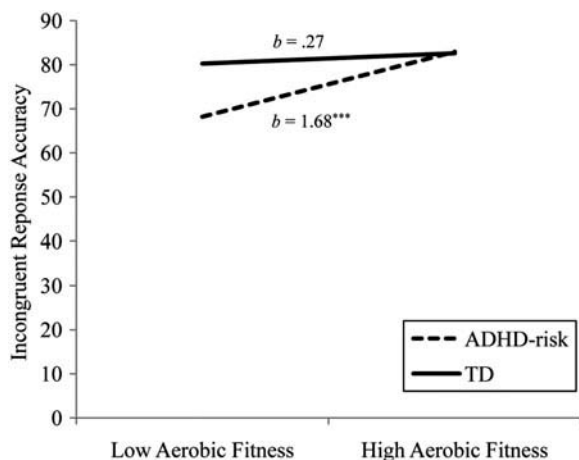


FIGURE 1 Two-way interaction of aerobic fitness and ADHD-risk status predicting incongruent response accuracy. Note: ADHD = attention deficit hyperactivity disorder; TD = typically developing. *** $p < .001$.

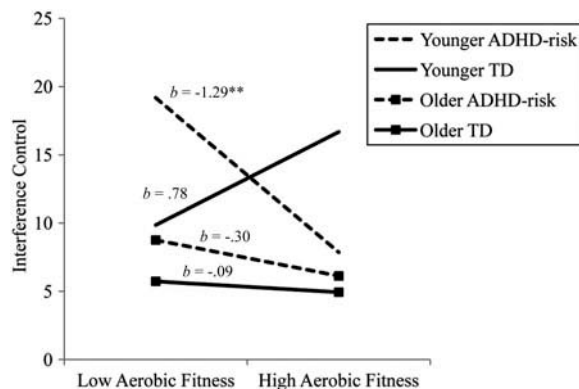


FIGURE 2 Three-way interaction of aerobic fitness, ADHD-risk status, and age predicting interference control. Note: ADHD = attention deficit hyperactivity disorder; TD = typically developing. ** $p < .01$.

DISCUSSION

We examined the association between aerobic fitness and inhibition in a sample of young children with and without risk for developing ADHD. As expected, bivariate correlations revealed that higher levels of aerobic fitness were associated with better overall performance across conditions of the flanker task. These results correspond with previous findings that higher fit TD children demonstrate superior performance than less fit peers (Hillman et al., 2009; Wu et al., 2011). The present study enriches the knowledge base by extending this work to a sample of young children with and without ADHD risk.

Our results suggest that the relation between aerobic fitness and inhibition (as measured by incongruent response accuracy) varies as a function of ADHD-risk status. Specifically, aerobic fitness and incongruent response accuracy were positively associated only for children identified as ADHD risk. These findings support Diamond and Lee's (2011) assertion that fitness may be more beneficial for individuals with known executive function deficits, such as children with ADHD risk, than those without such deficits. Diamond and Lee further contended that engaging in activities that facilitate executive function development (e.g., improving aerobic fitness) during early childhood can reduce the gap between TD children and those with deficient executive function. Our findings support this contention in that children of higher fitness had similar levels of incongruent response accuracy regardless of ADHD-risk status, whereas those with ADHD risk and lower fitness appear to have an inhibition deficit.

A significant three-way interaction between fitness, status, and age was observed for interference control. The association between aerobic fitness and interference control was significant only for younger children with ADHD risk, for whom higher levels of aerobic fitness were associated with better interference control. For younger children with

ADHD risk, the magnitude of the association between fitness and interference control was significantly different than the association for both younger and older TD children. However, the magnitude of this association for younger children with ADHD risk was not statistically different from older children with ADHD risk. Given findings that mechanisms promoting brain development (e.g., aerobic fitness) may have a greater impact in earlier stages of development when neuroplasticity is greater (Mundkur, 2005), it is possible that aerobic fitness is beneficial for interference control in both younger and older children with ADHD risk; however, the effects in the current study were apparent only in younger children.

Interactive effects were not observed in the congruent task condition. The congruent task condition involves limited interference and thus places fewer demands on executive function and frontal lobe systems. As researchers have speculated that executive function deficits in children with ADHD result from frontal lobe abnormalities (Krain & Castellanos, 2006), it is possible that when little demand is placed upon the frontal lobe systems, children with ADHD risk can perform similarly to TD peers. In contrast, when greater demands are placed on the frontal lobe systems, children with ADHD risk are likely to exhibit difficulty in accurate task completion, and thus benefit from the increased frontal lobe functioning associated with aerobic fitness (Voss et al., 2011). Therefore, the impact of aerobic fitness on inhibition is possibly most apparent on tasks making significant demands on the frontal lobe and executive function systems.

These promising findings must be interpreted in light of study limitations. First, our study was cross-sectional. Future research utilizing longitudinal designs to better understand how fitness may differentially influence inhibition development in children with ADHD or ADHD risk relative to TD children is necessary. Second, although our sample was fairly representative and diverse for the geographic regions involved (approximately 32% non-White), there were insufficient numbers of participants within non-White racial subgroups to pursue separate analyses by race/ethnicity. Third, our sample consisted of children at risk for, but not necessarily diagnosed with, ADHD. Thus, it is difficult to know whether our results will generalize to children who meet full diagnostic criteria for ADHD or those with more severe symptomatology. Finally, our findings stem from a lab-based cognitive task. Replication employing ecologically valid assessments of inhibition is warranted.

CONCLUSION

Regardless of ADHD-risk status, children who were more aerobically fit exhibited better inhibition on a flanker task as measured by the congruent task condition. When greater

demands on executive function were required, the relation between aerobic fitness and inhibition varied as a function of ADHD-risk status. Specifically, better aerobic fitness was associated with better inhibition for children with ADHD risk, such that inhibition appeared normalized. This association was especially salient for inference control in the younger participants in the sample. Taken together, these findings highlight the potential for aerobic fitness intervention as a pathway for addressing executive functioning impairment in children in the earliest school years who possess ADHD risk.

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