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Human Kinetics
ORIGINAL RESEARCH

# The Effects of Aerobic Versus Cognitively Demanding Exercise Interventions on Executive Functioning in School-Aged Children: A Cluster-Randomized Controlled Trial

**Anna Meijer,[1] Marsh Königs,[2] Irene M.J. van der Fels,[3] Chris Visscher,[3] Roel J. Bosker,[3] Esther Hartman,[3] and Jaap Oosterlaan[1,2]**
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The authors performed a clustered randomized controlled trial to investigate the effects of an aerobic and a cognitively demanding exercise intervention on executive functions in primary-school-age children compared with the regular physical education program ($N = 856$). They hypothesized that both exercise interventions would facilitate executive functioning, with stronger effects for the cognitively demanding exercise group. The interventions were provided four times per week for 14 weeks. Linear mixed models were conducted on posttest neurocognitive function measures with baseline level as covariate. No differences were found between the exercise interventions and the control group for any of the measures. Independently of group, dose of moderate to vigorous physical activity was positively related to verbal working memory and attention abilities. This study showed that physical exercise interventions did not enhance executive functioning in children. Exposure to moderate to vigorous physical activity is a crucial aspect of the relationship between physical activity and executive functioning.

***Keywords:*** cognition, moderate to vigorous physical activity, physical activity, RCT

The current increased prevalence of a sedentary lifestyle among children is alarming (Gabel et al., 2016; Tomkinson, Lang, & Tremblay, 2019; Tremblay et al., 2011). The majority of children do not even come close to the recommended 60 min of moderate to intense physical activity per day (Verloigne et al., 2012; World Health Organization, 2010). The evident lack of physical activity among children is worrisome in the light of evidence on the beneficial effects of physical activity, with physical activity leading to lower risk of Type 2 diabetes, cardiovascular disease, and obesity, as well as greater bone health (Janssen & LeBlanc, 2010). Moreover, recent evidence indicates that physical activity also has important neurocognitive benefits (de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Donnelly et al., 2016).

Findings from fundamental neuroscience (e.g., animal and biomedical studies) have identified several underlying mechanisms which may explain the beneficial effects of physical activity on neurocognitive functioning. A single bout of physical activity has been shown to directly enhance cerebral blood flow and to trigger the upregulation of neurotransmitters (e.g., epinephrine and dopamine; Dishman et al., 2006; Querido & Sheel, 2007). Prolonged physical activity triggers the release of neurotrophic factors (e.g., brain-derived neurotrophic factor and neural growth factor) and boosts neural blood vessel formation and neurogenesis (Dishman et al., 2006; Swain et al., 2003). These neural mechanisms are known to elicit neuroplasticity in the structure and function of brain areas that support neurocognitive functioning (Vaynman & Gomez-Pinilla, 2006). Despite the fact that most research concerning the intensity of physical activity is focused on the acute effects of physical activity, studies have shown that moderate to vigorous physical activity (MVPA) has the largest beneficial effects on neurocognitive functioning, and both light and vigorous physical activity have smaller effects (Colcombe et al., 2004; de Greeff et al., 2018; McMorris & Hale, 2012; Pesce, 2012). Thus, regular MVPA during childhood and adolescence may enhance neurocognitive functioning (Khan & Hillman, 2014).

It is further hypothesized that the involvement of high cognitive demands during exercise further boosts the beneficial effects of physical activity, either through performing complex motor exercises (that require cognitive control) or exercises that also involve cognitive engagement, for example, through the use of complex rules that need to be applied during the exercises. Such cognitive demands may enhance brain connectivity by axonal arborization or increases in the cell density between brain structures that are involved in both motor and cognitive functioning, in that way facilitating neurocognitive performance (Best, 2010; Tomporowski, McCullick, Pendleton, & Pesce, 2015). Hence, both the intensity of physical activity and the cognitive demands involved might be important factors in the effects of physical activity on neurocognitive functioning (Pesce, 2012; Tomporowski & Pesce, 2019).

Among the various domains of neurocognitive functioning, attention, interference control, and working memory are considered among the most relevant functions for the effects of physical activity (Best, 2010; de Greeff et al., 2018; Verburgh, Scherder, van Lange, & Oosterlaan, 2014). Executive functions (e.g., interference control and working memory) facilitate reasoning, problem solving, and planning (Collins & Koechlin, 2012; Salthouse, 2005). Lower-level neurocognitive functions (e.g., information processing and attention)

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are considered prerequisites for these executive functions. Executive functions are highly relevant for child development and are important predictors of behavioral functioning, academic achievement, and even other outcomes such as social well-being, health, wealth, and quality of life (Diamond & Lee, 2011).

Recent meta-analyses concerning the effects of physical activity on neurocognitive functioning in children indicated small to moderate effects of prolonged exercise on executive functioning (Alvarez-Bueno et al., 2017; de Greeff et al., 2018; Singh et al., 2018; Vazou, Pesce, Lakes, & Smiley-Oyen, 2019). Meta-analyses that differentiated between aerobic and cognitively demanding exercise showed larger effects for exposure to a combination of aerobic and cognitively demanding exercise compared to the sole exposure to one type of exercise (de Greeff et al., 2018; Vazou et al., 2019). However, only three randomized controlled trials (RCTs) included in these meta-analyses have directly compared the effects of aerobic and cognitively demanding exercise, the so-called head-to-head comparisons studies (Egger, Benzing, Conzelmann, & Schmidt, 2019; Koutsandreou, Wegner, Niemann, & Budde, 2016; Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). These three studies all showed beneficial effects of physical activity on executive functioning. More specifically, Schmidt et al. (2015) showed only improvement on executive functioning tasks in children assigned to cognitively demanding exercises but not in children who participated in aerobic exercises, whereas Koutsandreou et al. (2016) observed improvement in both exercise interventions and showed that the increase in performance was larger for the complex motor exercises group compared to the aerobic exercise group. In line with these findings, Egger et al. (2019) showed that a combination of aerobic and cognitively demanding exercises increases children's executive functioning and mathematic performances, whereas children who participated in aerobic or cognitively demanding exercise intervention only remained unaffected. The studies by Koutsandreou et al. (2016), Schmidt et al. (2015), and Egger et al. (2019) suggest that incorporating high cognitive demands during exercise could be the most promising method to enhance executive function in children. Nevertheless, the generalizability of the currently available evidence is questionable because conclusions are based on only three studies of which all studies focused on limited aspects of executive functioning (i.e., working memory, set shifting, and inhibition; Egger et al., 2019 and Schmidt et al., 2015, and working memory; Koutsandreou et al., 2016), and lower-level neurocognitive functions were not taken into account. This is in line with the recommendations of an international expert panel advocating that there is a need for more well-designed RCTs to gain better insight into the causal effects of exercise on executive function in children (Singh et al., 2018).

In the present clustered RCT, we investigated the effects of a school-based aerobic intervention and a cognitively demanding exercise intervention on executive functions in primary school-aged children. Three groups of children were compared: an aerobic exercise intervention group, a cognitively demanding exercise intervention group, and a control group. The direct comparison of the aerobic and cognitively demanding exercise interventions allowed us to determine whether the beneficial effects of physical activity more heavily depend on the aerobic or rather on the cognitively challenging components of physical activity. We used a set of neurocognitive functioning measures aimed at measuring both executive functioning (i.e., working memory, motor inhibition, and interference control) and lower-level neurocognitive functions (information processing and attention), facilitating a broader view on the effect of physical exercise on neurocognitive functioning. We hypothesized that aerobic exercise and cognitively demanding exercise both act to facilitate neurocognitive functioning. Nevertheless, based on the results of Egger et al. (2019), Koutsandreou et al. (2016), and Schmidt et al. (2015), we expected that the cognitively demanding exercise intervention would result in greater improvement on tasks of neurocognitive functioning. Additionally, we expected that children with lower baseline levels of executive functioning have greater potential for improvement and therefore would benefit more from the interventions compared to children with higher baseline levels of functioning (Diamond & Ling, 2016). Furthermore, we hypothesized that children being exposed to a higher dose of MVPA during the physical education lessons would show greater improvements in executive functioning compared to those exposed to lower doses. To adjust for background exposure to MVPA, we explored whether participation in organized sports outside the school environment contributes to the effects of the intervention. The results of this study are highly relevant for educational and health care policy makers and contribute to our knowledge on the role of physical activity in improving children's cognitive potential.

# Methods

## Study Design and Randomization Process

The current study is a cluster RCT. A statistical power analysis was performed to determine the number of schools required to demonstrate a difference of $d = 0.40$ between the two exercise conditions (average cluster size = 25; power = 0.71; $\alpha = .05$; two-tailed testing; intraclass correlation = .10, Spybrook, 2011). This analysis revealed that a minimum of 40 classes across 20 schools was required for this between-group comparison. To take into account the possibility that schools might withdraw from participation, 48 classes of 24 schools were included. Participating schools were sorted into school pairs based on school size. A two-step cluster-randomization was determined, in which the first step involved random allocation of a school pair to one of two exercise interventions (aerobic exercise intervention vs. cognitively demanding exercise intervention). In the second step, it was randomly determined which class (third or fourth grade) would receive the intervention and which class would serve as the control group within the first school of the school pair. The other paired school received the same intervention, but now the intervention groups were assigned to the other grade. This two-step randomization strategy was used to stratify age (Grade) and control for demographic factors and school setting. Randomization was performed by one of the authors not involved in school recruitment (R.J.B.).

## Participants

Data were collected between September 2016 and June 2017. Just before the start of the study, two schools withdrew permission due to practical organizational considerations, leaving a total of 22 primary schools contributing data to the study. Principals of the schools and parents or guardians of 891 children gave written consent for participation of their children. To limit the chance that children did not understand the task instructions, children were excluded if they had an estimated IQ < 70 ($n = 10$). Participating children were excluded from further analyses if they did not attend the neurocognitive assessment during the baseline measurement

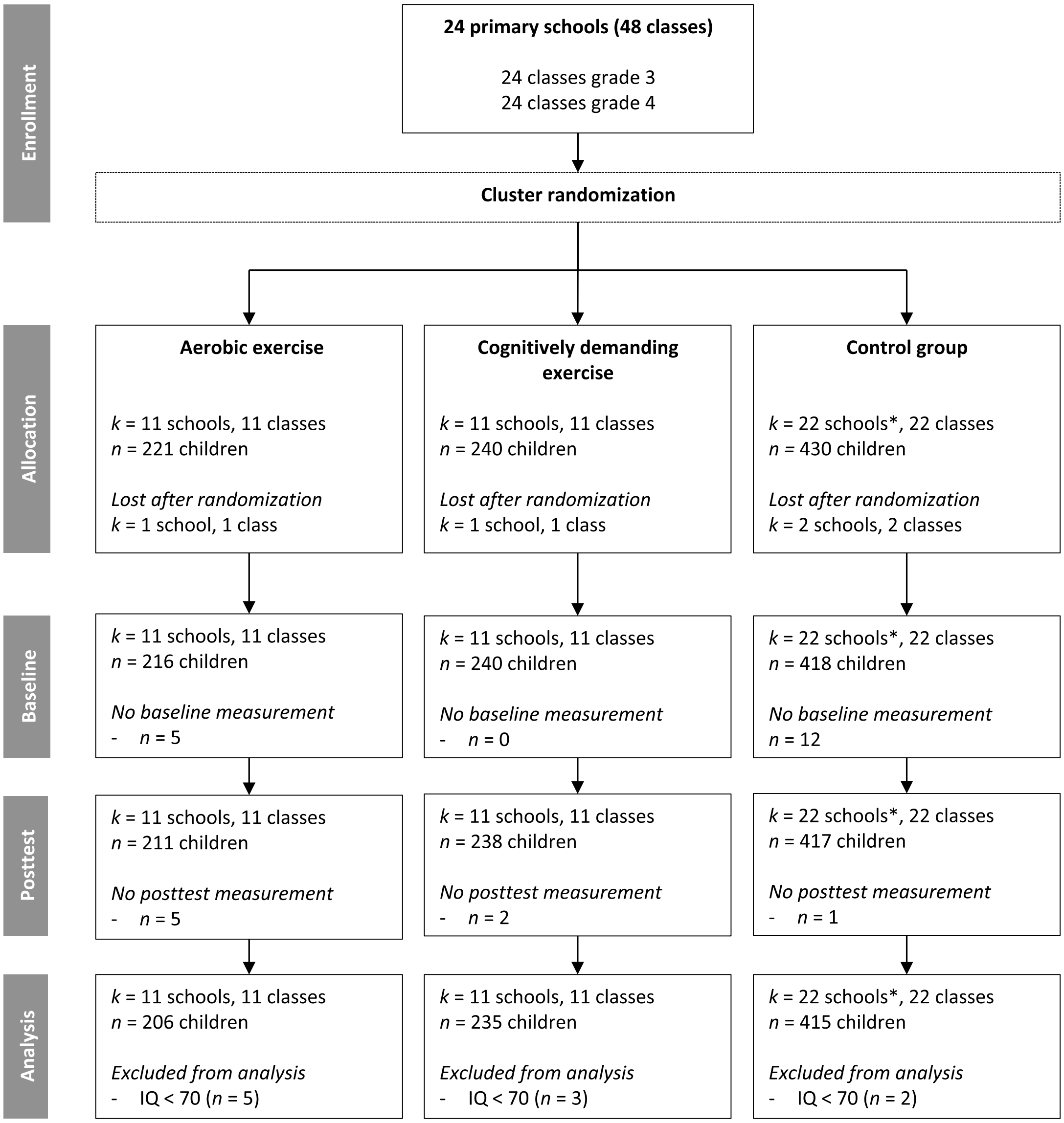

**Figure 1** — Flow diagram of the cluster-randomized controlled trial and the total number of children in each stage of the study. *Same schools as schools participating in the aerobic and the cognitively demanding exercise intervention.

($n = 17$) or posttest ($n = 8$). The flow diagram in Figure 1 shows the total number of children in each stage of the study.

## Interventions

The aerobic exercise intervention and the cognitively demanding exercise intervention were implemented as a physical education program that was provided four times per week for 14 weeks (De Bruijn et al., 2020; van der Fels et al., 2020). This program replaced other lessons (among which were two regular physical education lessons per week). Both the interventions were designed by academic experts in Human Movement Sciences and experienced physical education teachers, who were well acquainted with the regular physical education curriculum. In that way, it was ensured that the aerobic exercise intervention and the cognitively demanding exercise intervention would differ from the regular physical education curriculum in terms of their aerobic and cognitively demands, respectively. The interventions were provided by trained and certified physical education teachers. The lessons consisted of a warm-up phase of 10 min and a core phase of 20 min. The aerobic exercise intervention consisted of activities specifically designed to target moderate-to-vigorous intensity while avoiding high cognitive demands. The focus was on highly repetitive and automated exercises, such as circuit training, relay games, playing tag, and individual activities like running or doing squats. The cognitively demanding exercise intervention consisted of team games or exercises that require complex coordination of movements, strategic play, cooperation between children, anticipating the behavior of teammates or opponents, and dealing with changing task demands (Best, 2010). Children played adapted versions of games such as dodgeball, basketball, or soccer to specifically target executive functions (Tomporowski, McCullick, & Pesce, 2015). Complex rules were included in the games so that children were constantly challenged to think about their actions and movements. The complexity of the games and exercises increased during the intervention period in order to sustain high cognitive demands during the course of the physical education program. Children in the control group followed their regular physical education lessons twice a week. Due to the obvious differences between the exercise interventions and control group, blinding of participants was not possible.

## Neurocognitive Functioning Tasks

All neurocognitive tasks and corresponding outcome measures are listed in Table 1.

## Attention Network Test

An adapted version of the Attention Network Test was used to measure information processing, alerting attention, spatial attention, and interference control (Rueda et al., 2004). In this task, target stimuli consisting of an arrow pointing left or right were presented on a computer screen. Children were instructed to respond as quickly as possible to the direction of a target stimulus by pressing the corresponding button. The target stimuli were flanked by two distractors on each side, which could be neutral (flat lines without spatial information), congruent (identical arrows pointing to the same direction as the target), or incongruent (identical arrows pointing to the other direction than the target). Target stimuli were preceded by three types of warning cues: a central cue in the middle of the screen, a spatial cue indicating the position of the upcoming target, or no cue. Trials started with the presentation of a fixation cross, which was followed by a cueing period (145 ms), an interstimulus period during which the centrally located fixation cross is presented again (395 ms), and finally the presentation of the target stimulus (the arrow with flankers) that is presented just above or below the fixation cross. The target stimulus remained on the screen until a response was recorded with a maximum response time of 645 ms. During these trials, there were three cue conditions (no cue, central cue, and spatial cue trials) and three target conditions (neutral, congruent, and incongruent target trials). All conditions were equally represented, and all trials were counterbalanced and presented in predefined random order. Trials were presented in three blocks of 72 trials and were preceded by a practice block of 24 trials. As lapses of attention cause extreme slow responses that inflate information processing speed, we used so-called ex-Gaussian modeling of reaction time distributions to calculate the contribution of extreme slow responses (i.e., lapses of attention, tau; Lacouture & Cousineau, 2008). Estimates of tau were obtained from fitting the ex-Gaussian distribution to the reaction times data in which tau represents the exponential component and characterizes the slow reaction times in the tail of the distribution. Background information on ex-Gaussian modeling and full explanation of the mathematical procedure is provided elsewhere (Lacouture & Cousineau, 2008; Van Zandt, 2000; Whelan, 2008).

## Digit Span

The forward and backward conditions of the Digit Span Task were used to measure verbal working memory (Wechsler

**Table 1 Description and Operationalization of Neurocognitive Measures**

| Task | Measure | Description | Dependent variable |
|---|---|---|---|
| ANT | Information processing | The speed of responding to target appearance | Mean reaction time (ms) on neutral trials |
| | Tau | Lapses of attention | The average of the exponential component of the fitted ex-Gaussian curve, reflecting the influence of extremely slow responses (lapses of attention) on information processing |
| | Alerting attention | The speed of achieving an alert state | The difference in mean reaction time (ms) between central cue trials and no cue trials |
| | | The accuracy of achieving an alert state | The difference in percentage of correct responses on central cue trials and no cue trials |
| | Spatial attention | The speed of spatially orienting to information | The difference in mean reaction time (ms) between spatial cue trials and central cue trials |
| | | The accuracy of spatially orienting to information | The difference in the percentage of correct responses on central cue trials and spatial cue trials |
| | Interference control | The speed of suppressing irrelevant information | The difference in mean reaction time (ms) between incongruent trials and congruent trials |
| | | The accuracy of suppressing irrelevant information | The difference in the percentage of correct responses on incongruent trials and congruent trials |
| DS | Verbal short-term memory | The ability to hold verbal information in short-term memory | The product of the number of correct responses and the highest span reached in the forward condition[a] |
| | Verbal working memory | The ability to manipulate verbal information in working memory | The product of the number of correct responses and the highest span reached in the backward condition[a] |
| GT | Visuospatial short-term memory | The ability to hold visuospatial information in short-term memory | The product of the number of correct responses and the highest span reached in the forward condition[a] |
| | Visuospatial working memory | The ability to manipulate visuospatial information in working memory | The product of the number of correct responses and the highest span reached in the backward condition[a] |
| SST | Motor inhibition efficiency | The latency of an inhibitory process | The mean reaction time (ms) calculated for correct responses on GO trials subtracted by the average delay between the GO and STOP signal (ms) |

*Note*. ANT = Attention Network Test; DS = Digit Span; GT = Grid Task; SST = Stop Signal Task.
[a] Calculation based on Kessels, Van Zandvoort, Postma, Kappelle, and De Haan (2000).

Intelligence Scale for Children III; Wechsler, 1991). Digit Span Task requires children to repeat a sequence of numbers presented auditorily (one stimulus per second) by the examiner in the order of presentation (forward condition) or reversed order (backward condition). Trial difficulty was determined by length of the sequence, which increased with one digit every other trial. The task was terminated after two consecutive incorrect responses on trials with the same difficulty level.

## Grid Task

Visuospatial working memory was assessed using the forward and backward condition of the computerized Grid Task developed by Nutley, Söderqvist, Bryde, Humphreys, and Klingberg (2009). In this task, a sequence of yellow dots is presented on a four by four grid (one stimulus per second). Children were required to repeat the sequence in the order of presentation (forward condition) or reversed order (backward condition) by clicking on the relevant locations in the grid. Trial difficulty was determined by both the number of yellow dots and by the trajectory of the yellow dots on the grid (Nutley et al., 2009). Each difficulty level consisted of two trials. The task was terminated after two consecutive incorrect responses on trials with the same difficulty level.

## Stop Signal Task

The Stop Signal Task was used to measure motor inhibition (Logan, 1994). This task involves Go trials and Stop trials. Go trials consisted of an airplane either pointing to the right or left side of the computer screen. Stop trials were identical to Go trials but with a stop signal superimposed on the airplane. Children were instructed to respond as quickly as possible to Go trials by pressing the corresponding button and to inhibit the motor response when the stop signal is presented. The stop signal was presented with an initial delay of 175 ms after the onset of the stimulus and was lengthened or shortened by 50 ms on the next Stop trial when the response was correct (successful motor response inhibition) or incorrect (failed motor response inhibition), respectively. This procedure yielded approximately 50% successful inhibitions and 50% failed inhibitions. To assess motor inhibition, stop signal reaction time (SSRT) was calculated by subtracting average delay between the GO and STOP signal across all STOP trials from the mean reaction time calculated for correct responses on GO trials. Trials were presented in three blocks of 64 trials (49 Go trials and 15 Stop trials) and were preceded by two practice blocks of eight and 24 trials.

## Wechsler Intelligence Scale for Children

Full-scale intelligence quotient (IQ) was estimated by a two-subtest short form (Information and Block Design) of the Wechsler Intelligence Scale for Children III (WISC-III; Wechsler, 1991). This subset has good reliability and validity ($r_{xx} = .90$, $r = .85$; Sattler, 2001)

## Demographic Variables

Additional information was collected by parent questionnaires to asses demographic information (sex, age, socioeconomic status [SES]), and information on participation in sports. The SES was defined as the average level of parental education ranging from 0 (*no education*) to 7 (*postdoctoral education*) (Statistics Netherlands, 2006). Participation in sports was defined as weekly participation in organized sports in minutes, not involving physical education, transport to school, and playing outside.

## MVPA

Accelerometers were used to measure the amount of MVPA in the three intervention arms (ActiGraph GT3x+; ActiGraph, Pensacola, FL). Accelerometer data were collected during two designated physical education lessons, one during the first week of the intervention period and one during the last week of the intervention period. Approximately 20 children were randomly selected from the participating children in each class and were provided with an accelerometer on the right hip (Evenson, Catellier, Gill, Ondrak, & McMurray, 2008). Participants were instructed to move as usual during the physical education lessons. Accelerations were determined in three directions at 100 Hz. Only data from the vertical axis were used (Evenson et al., 2008). Analyses were performed using the ActiLife software package (version 6.8.2; Pensacola, FL). An epoch length of 1 s and a cutoff point of >2,296 counts/min was used as a measure for MVPA (Evenson et al., 2008; Trost, Loprinzi, Moore, & Pfeiffer, 2011). The average time in MVPA per lesson (in minutes) over the two lessons was calculated for each participant. The total exposure to MVPA (in minutes) was calculated by the product of the average time in MVPA per lesson and the total number of received lessons for both the interventions and 28 lessons for the control group (i.e., two times per week for 14-week long).

## Study Procedures

The current study was part of the “Learning by Moving” trial, in which effects of an aerobic exercise intervention and a cognitively demanding exercise intervention were determined in primary school children on physical and cognitive outcomes, academic achievement, and brain structure and function (De Bruijn et al., 2020; van der Fels et al., 2020). All participating children were tested within a period of 2 weeks before and after the 14-week period in which the interventions took place. The neurocognitive assessment was individually administered during the school day by trained nonblinded examiners using standardized protocols. To prevent tiredness and distraction, the cognitive tasks were administered in two sessions performed on separate days, with a duration of 30–35 min per session. The neurocognitive tasks were assessed in the same order for all participants (Session 1: Stop Signal Task, DS, WISC-III Block Design; Session 2: Attention Network Test, VWSM, WISC-III Information). The order of sessions and tests was identical for both pretest and posttest assessments, except for the WISC-III tasks, which were administered only at pretest. This study was approved by the ethical board of the Vrije Universiteit Amsterdam (Faculty of Behavioral and Movement Sciences) and registered in the Netherlands Trial Register (#NTR5341).

## Data Analysis

Preprocessing steps and statistical analysis were performed in IBM SPSS Statistics (version 25.0; SPSS IBM, New York, NY) and in R for Statistical Computing (R Foundation for Statistical Computing, Vienna, Austria). Outliers ($z \le -3.29$ or $\ge 3.29$) were winsorized (Field, 2013). To determine if data were normally distributed, histograms were visually inspected and values of skewness and kurtosis were calculated. Nonattendance of participating children during one of the assessment days resulted in missing data.

Prevalence of missing values ranged between 0% and 10% for all measured variables. When the total baseline or posttest measurement was missing, we excluded the child in further analyses ($n = 17$). Other missing values at random were replaced by multiple imputation (Sterne et al., 2009). For the measures derived from the Attention Network Test, individual scores below chance level were discarded from further analysis (as determined by the upper endpoint of the 95% confidence interval around a random performance of 50% accuracy; $n = 14$). All neurocognitive measures were recoded so that higher scores indicate better performance. The three groups were compared on demographic variables (age, sex, grade, body mass index [BMI], and SES) and on IQ, MVPA, and sports participation using a one-way analysis of variance or $\chi^2$ test, where appropriate. Significant group effects were further explored with pairwise group comparisons.

To reduce the number of neurocognitive measures and to enhance their reliability, principal component analysis (PCA) was performed on all measures resulting from the neurocognitive tests assessed at baseline (Table 2), to derive composite measures, here referred to as neurocognitive functioning components (Meijer et al., 2020). To this end, data were subjected to PCA with varimax rotation using the psych-package in R (Vienna, Austria; Revelle, 2018). The scree plot was visually inspected to select the components that were retained and subjected to further analysis. Factor loadings of $r > .30$ were considered relevant for labeling the components. The resulting model was also used to calculate the component scores on the posttest neurocognitive functioning components.

All further analyses were performed in IBM SPSS Statistics (SPSS IBM). To determine the main effects of group (i.e., aerobic exercise group, cognitively demanding exercise group, control group) on the change in neurocognitive functioning components, while also accounting for the clustered structure of our data (children clustered in school classes), mixed model analyses were conducted. More specifically, linear regression models were conducted in which the posttest executive functioning components were used as dependent variables and group as predictor. A random intercept was added to the model for school class. The baseline score on the corresponding neurocognitive functioning component was included as a covariate in each model. Demographic variables (sex, grade [three or four], age, and SES) were included as covariates using a stepwise backward selection approach, providing a data-driven selection of relevant covariates for each dependent variable. We additionally investigated the interaction between the effect of group and (a) significant demographic covariates, (b) significant baseline scores on the corresponding executive functioning component, (c) the intensity of the exercise intervention in the two intervention groups and the physical education lessons in the control group (exposure to MVPA), or (d) participation in organized sports. Effect sizes were calculated for all relationships and were interpreted using Cohen's guidelines, including definitions of small ($d = 0.2–0.5$), medium ($d = 0.5–0.7$), and large effect sizes ($d > 0.7$; Cohen, 1988).

For each executive functioning component showing a significant relation with group, we explored which specific neurocognitive measures contained in the component were responsible for the observed relation. Mixed model linear regression models were conducted in which the relevant neurocognitive measures (see Table 1 for an overview) were used as dependent variables and group was included as predictor. For these regression analyses, we used the same strategy as described for the regression models at component level. Level of significance was set at .05 in all analyses (two-sided).

## Results

Group characteristics are displayed in Table 2. It was observed that 12.4% and 3.0% of the participants were overweight and

**Table 2 Group Characteristics of the Aerobic Exercise, Cognitively Demanding Exercise, and Control Groups**

| Group characteristic | Aerobic exercise (*n* = 206) | Cognitively demanding exercise (*n* = 235) | Control group (*n* = 415) | Statistic | *p* | Post hoc tests |
|---|---|---|---|---|---|---|
| Sex, *n* (%girls) | 104 (50.49%) | 126 (53.62%) | 206 (49.64%) | $\chi^2(2) = 0.97$ | .615 | |
| Age (years), *M* (*SD*) | 9.30 (0.65) | 9.04 (0.59) | 9.16 (0.67) | *F*(2, 853) = 9.33 | <.001 | Aerobic > Control, Cognitive |
| BMI (kg/m$^2$), *M* (*SD*) | 16.81 (2.14) | 16.79 (2.29) | 16.53 (2.26) | *F*(2, 853) = 1.54 | .215 | |
| Underweight, *n* (%)[a] | 3 (1.46%) | 0 (0%) | 8 (1.93%) | $\chi^2(2) = 5.98$ | .426 | |
| Overweight, *n* (%)[a] | 27 (13.11%) | 29 (12.34%) | 45 (10.84%) | $\chi^2(2) = 5.98$ | .426 | |
| Obesity, *n* (%)[a] | 4 (1.94%) | 8 (3.40%) | 11 (2.65%) | $\chi^2(2) = 5.98$ | .426 | |
| Grade 3, *n* (%) | 93 (45.15%) | 122(51.91) | 222 (53.49%) | $\chi^2(2) = 53.94$ | .140 | |
| IQ, *M* (*SD*) | 100.13 (12.90) | 103.49 (14.00) | 99.97 (13.29) | *F*(2, 853) = 5.71 | .003 | Cognitive > Aerobic, Control |
| SES, *M* (*SD*)[b] | 4.36 (0.86) | 4.68 (0.98) | 4.46 (1.00) | *F*(2, 853) = 6.43 | .002 | Cognitive > Aerobic, Control |
| MVPA per lesson (min), *M* (*SD*) | 12.25 (3.03) | 9.45 (2.52) | 10.73 (3.59) | *F*(2, 853) = 42.14 | <.001 | Aerobic > Control > Cognitive |
| Total MVPA exposure (min), *M* (*SD*) | 591.73 (142.93) | 448.31 (128.34) | 300.54 (100.54) | *F*(2, 853) = 422.74 | <.001 | Aerobic > Cognitive > Control |
| Sports participation (min/week), *M* (*SD*) | 148.01 (131.62) | 147.40 (111.94) | 151.45 (101.21) | *F*(2, 853) = 0.83 | .439 | |

*Note*. BMI = body mass index; IQ = intelligence quotient; MVPA = moderate to vigorous physical activity; SES = socioeconomic status.
[a] According to the reference values by Cole and Lobstein (2012). [b] The average level of parental education ranged from 0 (*no education*) to 7 (*postdoctoral education*).

obese, respectively, which parallels recent prevalence rates for the Dutch pediatric population (Cole & Lobstein, 2012; Volksgezondheid en zorg, 2018). Children in the aerobic and cognitively demanding exercise group attended on average 3.2 intervention lessons per week. Groups differed in age, $F(2,853) = 9.33$, $p < .001$, IQ, $F(2,853) = 5.71$, $p = .003$, SES, $F(2,853) = 6.43$, $p = .002$, exposure to MVPA per lesson, $F(2,853) = 42.14$, $p < .001$, and total exposure to MVPA, $F(2,853) = 422.74$, $p < .001$. Children in the aerobic exercise group were slightly older compared to the children in the cognitively demanding exercise group and control group, which was due to the dropout of two schools after randomization, which both delivered Grade 3 classes to the aerobic exercise intervention. Children in the cognitively demanding exercise group had somewhat higher IQs and SES compared with the children in the aerobic exercise group as well as the control group. As expected, average time spent in MVPA per lesson was higher in the aerobic exercise group compared to the control group and the cognitively demanding exercise group. In addition, time spent in MVPA was significantly higher in the control group than in the cognitively demanding exercise group. However, if we take the frequency of the interventions into account, the aerobic exercise group was exposed to the highest total estimated time of MVPA, and the control group received the lowest exposure to MVPA. An overview of the results of all neurocognitive measures per group is presented in Table 3.

## PCA

The PCA extracted a total of six components from the neurocognitive measures, which together explained 70% of the total variance (see Table 4). The executive function components were labeled as follows: (a) information processing and control (information processing speed, lapses of attention, and motor inhibition efficiency), (b) interference control (speed and accuracy of interference control), (c) attention accuracy (accuracy of alerting attention and spatial orientation), (d) visuospatial working memory (visuospatial working memory and visuospatial short-term memory), (e) verbal working memory (verbal short-term memory and verbal working memory), and (f) attention efficiency (speed of alerting attention and spatial attention to information).

## Intervention Effects

Table 5 shows the results of the mixed model analyses assessing the effects of group on the executive functioning components. No differences were found between the two exercise intervention groups and the control group for any of the components. These results indicate that there is no evidence for any differential effects of the aerobic exercise or cognitively demanding exercise intervention on the executive function components compared to the control group, nor is there evidence for differential effects of the two interventions on the executive function components.

## Interaction Effects Between Group and Covariates

To investigate whether the effects of group on the neurocognitive functioning components were influenced by other factors, we tested the interaction between groups and (a) each of the demographic characteristics that remained significant in the final models (i.e., sex, grade, SES), (b) baseline level of functioning on the corresponding neurocognitive functioning component, (c) the intensity of the exercise interventions (exposure to MVPA per lesson), and (d) participation in organized sports.

Demographic characteristics (sex, grade, and SES) that contributed to the models are listed in Table 5. Analysis aimed at these demographic characteristics showed no significant interactions between group and sex, grade, or SES.

Analysis aimed at baseline levels of executive functioning showed a significant interaction with group for the neurocognitive component interference control ($B = 0.062$, $p = .032$, $d = 0.06$). Children with higher interference control performance at baseline benefited more from the cognitively demanding intervention compared to the children in the control group. No other significant interactions were found between group and baseline level of functioning for any of the other neurocognitive functioning components.

Analysis aimed at the effects of exposure to MVPA per lesson showed the main effects of exposure to MVPA for the neurocognitive functioning components verbal working memory ($B = 0.028$, $p = .004$, $d = 0.09$) and attention efficiency ($B = 0.029$, $p = .007$, $d = 0.10$). Children with higher exposure to MVPA showed more improvement on verbal working memory and attention efficiency performance compared to children with lower exposure to MVPA. No significant interaction effects were found between group and exposure to MVPA for these components, indicating that the effects of exposure to MVPA on verbal working memory and attention efficiency applied to all groups. For the other components (information processing and control interference control, attention accuracy and visuospatial working memory), no significant main effects of exposure to MVPA or interactions between group and exposure to MVPA were found. Furthermore, no significant main effects were found for sports participation and group did not significantly interact with sports participation for any of the components.

# Discussion

In the present clustered RCT, we investigated the effects of school-based aerobic and cognitively demanding exercise on executive functions in a large sample of primary school-aged children. We hypothesized that aerobic exercise and cognitively demanding exercise would both facilitate executive functioning and that this effect would be stronger for children in the cognitively demanding exercise intervention (Egger et al., 2019; Koutsandreou et al., 2016; Schmidt et al., 2015). The main results of our study showed no significant effects of the two exercise interventions on executive functioning compared with the control condition and also no difference between the aerobic exercise intervention and cognitively demanding exercise intervention. Contrasting with our hypothesis about the role of baseline executive functioning (Diamond & Ling, 2016), the results indicate that children with higher interference control performance at baseline benefited more from the cognitively demanding intervention compared with children in the control group. We also investigated the role of intervention intensity (as reflected by the time spend in MVPA) and participation in organized sports. The results show that, independently of group, the exposure to MVPA was positively related to improved verbal working memory-related abilities and efficiency of attentional abilities after the intervention period. These findings suggest that exposure to higher levels of MVPA is beneficial for specific aspects of executive functioning in children. No significant effects were found for organized sports participation.

Our findings are in line with a recent expert panel review of high-quality studies that found that less than half of the studies report beneficial effects of physical activity on cognitive functioning in children, which led the panel to conclude that the evidence regarding

### Table 3 Performance of the Three Groups on the Neurocognitive Measures

| Neurocognitive measure | Description | Aerobic exercise (*n* = 206) | | Cognitively demanding exercise (*n* = 235) | | Control group (*n* = 415) | |
|---|---|---|---|---|---|---|---|
| | | Baseline | Posttest | Baseline | Posttest | Baseline | Posttest |
| Information processing | Information processing speed (MRT, ms)[a] | 636.68 (84.37) | 574.72 (80.19) | 646.61 (89.89) | 581.42 (87.93) | 654.83 (99.02) | 586.16 (90.62) |
| Lapses of attention | Tau[a] | 127.71 (45.24) | 116.82 (48.00) | 127.64 (45.07) | 115.37 (53.03) | 131.25 (48.85) | 119.75 (49.88) |
| Alerting attention | Speed of alerting attention (MRT, ms)[a] | –33.71 (30.13) | –38.19 (27.29) | –37.60 (33.91) | –44.59 (29.69) | –37.39 (31.14) | –42.76 (29.12) |
| | Accuracy of alerting attention (%correct) | –0.24 (2.82) | –0.22 (2.45) | –0.21 (3.13) | –0.53 (2.81) | –0.13 (3.06) | –0.14 (2.72) |
| Spatial attention | Speed of spatial attention (MRT, ms)[a] | –32.16 (31.63) | –27.35 (28.48) | –36.33 (31.22) | –24.30 (27.68) | –32.59 (30.95) | –24.37 (29.85) |
| | Accuracy of spatial attention (%correct) | 0.58 (2.80) | 0.35 (2.68) | 0.69 (3.12) | 0.27 (3.22) | 0.68 (2.82) | 0.07 (3.04) |
| Interference control | Speed of interference control (MRT, ms)[a] | 128.93 (59.94) | 84.75 (45.52) | 133.96 (66.41) | 84.67 (43.89) | 131.56 (62.35) | 84.67 (43.89) |
| | Accuracy of interference control (% correct) | –5.94 (6.00) | –5.23 (5.08) | –6.54 (6.80) | –5.31 (6.21 | –5.78 (6.21) | –4.87 (4.94) |
| Verbal working memory | Verbal short-term memory (Correct responses × Span) | 33.01 (12.73) | 35.42 (13.68) | 32.09 (12.52) | 36.80 (13.66) | 31.49 (12.55) | 34.08 (13.89) |
| | Verbal working memory (Correct responses × Span) | 14.11 (8.00) | 14.86 (9.26) | 15.04 (8.81) | 15.63 (9.22) | 14.14 (8.68) | 15.29 (8.98) |
| Visuospatial working memory | Visuospatial short-term memory (Correct responses × Span) | 56.95 (22.58) | 65.77 (25.42) | 60.25 (23.49) | 67.33 (26.62) | 60.43 (24.24) | 67.89 (25.18) |
| | Visuospatial working memory (Correct responses × Span) | 44.12 (21.58) | 49.99 (26.26) | 47.65 (24.96) | 52.12 (24.58) | 47.46 (21.92) | 52.29 (26.44) |
| Motor inhibition | Motor inhibition efficiency (SSRT, ms)[a] | 241.24 (43.88) | 230.05 (43.65) | 250.76 (51.76) | 237.94 (46.27) | 250.52 (50.75) | 237.29 (49.39) |

*Note*. Data are presented as *M* (*SD*). MRT = mean reaction time; SSRT = stop signal reaction time.

[a] Lower values reflect better performance.

**Table 4 Results of Principal Component Analysis on the Neurocognitive Measures (Baseline)**

| Neurocognitive measure | Component 1: Information processing and control | Component 2: Interference control | Component 3: Attention accuracy | Component 4: Visuospatial working memory | Component 5: Verbal working memory | Component 6: Attention efficiency |
|---|---|---|---|---|---|---|
| Information processing | 0.864 | | | | | |
| Lapses of attention | 0.841 | | | | | |
| Speed of alerting attention | | | | | | –0.775 |
| Accuracy of alerting attention | | | 0.860 | | | |
| Speed of spatial attention | | | | | | 0.824 |
| Accuracy of spatial attention | | | –0.850 | | | |
| Speed of interference control | | 0.845 | | | | |
| Accuracy of interference control | | 0.814 | | | | |
| Verbal short-term memory | | | | | 0.836 | |
| Verbal working memory | | | | | 0.793 | |
| Visuospatial working memory | | | | 0.803 | | |
| Visuospatial short-term memory | | | | 0.842 | | |
| Motor inhibition | 0.583 | | | | | |
| Eigenvalue | 1.923 | 1.502 | 1.501 | 1.465 | 1.385 | 1.354 |
| Percentage of variance explained by component | 14.800 | 11.500 | 11.400 | 11.100 | 10.600 | 10.400 |

*Note*. Please refer to Table 2 for a description of the measures; only factor loadings >.300 are presented.

**Table 5 Results of Linear Mixed Model Analysis Comparing the Three Groups on the Neurocognitive Function Components**

| Neurocognitive function component | Covariates[a] | Beta | *SE* | 95% CI | *p* | Cohen's *d* |
|---|---|---|---|---|---|---|
| 1 Information processing and control | Grade SES | 0.001 | 0.032 | [–0.062, 0.063] | .977 | 0.001 |
| 2 Interference control | Age, grade SES, and sex | –0.042 | 0.030 | [–0.101, 0.016] | .157 | 0.040 |
| 3 Attention accuracy | | –0.051 | 0.043 | [–0.137, 0.036] | .242 | –0.040 |
| 4 Visuospatial working memory | Age grade | –0.028 | 0.038 | [–0.106, 0.049] | .461 | –0.024 |
| 5 Verbal working memory | Grade SES | 0.032 | 0.044 | [–0.056, 0.121] | .465 | 0.028 |
| 6 Attention efficiency | | –0.002 | 0.046 | [–0.095, 0.090] | .959 | –0.002 |

*Note*. CI = confidence interval; SES = socioeconomic status.
[a] Covariates significantly related to the neurocognitive function component.

the effects of physical activity on cognitive functioning is currently inconclusive (Singh et al., 2018). Nevertheless, contrasting with the conclusions drawn in three recent meta-analyses summarizing the pertinent findings (Alvarez-Bueno et al., 2017; de Greeff et al., 2018; Vazou et al., 2019), our study did not show beneficial effects of physical activity on executive functioning. In addition, we did not find support for our hypothesis that the cognitively demanding exercise intervention would elicit greater improvement on tasks of executive functioning compared to the aerobic exercise intervention (de Greeff et al., 2018; Egger et al., 2019; Koutsandreou et al., 2016; Schmidt et al., 2015). Our findings contrast with earlier studies comparing these two types of exercise in primary school-aged children (Egger et al., 2019; Koutsandreou et al., 2016; Schmidt et al., 2015) that reported larger effects of cognitively demanding exercise interventions on working memory and set shifting. However, as in the current study, these studies also failed to find any significant effects on inhibition.

One possible explanation for not observing beneficial effects of physical activity on executive functioning in our study might be that the characteristics of our exercise interventions (intensity, session length, number of sessions offered and/or length of the intervention period) were not sufficient to influence executive functioning compared to the regular physical education lessons. Children in our aerobic exercise and cognitively demanding exercise intervention participated on average in 3.2 lessons per week. Although the number of lessons received was lower than the intended number of four lessons per week, children in our intervention still had a minimum of 60% increase in physical education lessons compared to the regular participation in physical education lessons (conservatively assuming that children in the control group participated in all regular classes). Furthermore, despite the fact that the total estimated time in MVPA was considerably higher for both our interventions compared to the control group, the intensity of our aerobic exercise intervention might not have been enough to evoke beneficial effects on executive functioning. Earlier analyses of the data gathered in our study showed that our two exercise interventions were also not successful in improving cardiovascular fitness (van der Fels et al., 2020). It could be argued that a change in cardiovascular fitness due to physical exercise would be a necessary condition for producing changes in the brain (de Greeff et al., 2018). Thus, the absence of beneficial effects of our interventions on cardiovascular fitness might explain why the interventions did not translate into improvements in neurocognitive functioning. Future research should determine the optimal frequency, duration, and/or intensity of exercise interventions to enhance cardiovascular fitness and in turn neurocognitive functioning in children.

In line with the idea that the intensity of physical activity triggers several physiological mechanisms that facilitate neurocognitive functioning and executive functioning in particular, we found that the time spent in MVPA was associated with some key aspects of neurocognitive functioning. Our results indicate that children with higher exposure to MVPA show greater improvement of verbal working memory and efficiency of alerting and orienting attention, neurocognitive functions that are crucial in, for example, academic achievement (Bull, Espy, & Wiebe, 2008; Diamond & Lee, 2011). The effects of MVPA were found across all three study groups, while no differences between the study groups were found. These findings may indicate that increased MVPA, which is the main target of aerobic exercise interventions, leads to beneficial effects on specific neurocognitive functions. This is in line with our previous cross-sectional study investigating the relationship between cardiovascular fitness and executive functioning, in which we found a positive relationship between cardiovascular fitness and specific neurocognitive components, including attentional functioning (Meijer et al. 2020). Possibly, the physiological mechanisms involved in MVPA act on a specific set of neurocognitive functions. More specifically, the effects of MVPA on the efficiency of alerting and orienting attention could possibly be explained by increased arousal levels that, in turn, lead to cumulative upregulation of epinephrine and dopamine levels (Dishman et al., 2006; Querido & Sheel, 2007). The findings with regard to MVPA do support the idea that the intensity of physical activity is an important factor in the effects of physical activity on executive functions. However, as we found no positive effects of the aerobic intervention, we may not have been able to reach the critical threshold of exposure to MVPA at group level in the aerobic intervention arm that is necessary to elicit beneficial effects on neurocognitive functioning.

Our study found no support for the idea that the effects of cognitively demanding exercise on executive functioning would be stronger than those of aerobic exercise. This raises the question of whether we were successful in creating the intended differences in terms of the cognitive demands exerted by the cognitively demanding and aerobic exercise intervention. It could be possible that the amount of cognitive demands in the aerobic exercise intervention was higher than intended. As we are not aware of an existing measure of cognitive engagement during physical activity, we could not assess the fidelity of this aspect of our interventions. However, the difference in terms of the cognitive demands exerted by the cognitively demanding and aerobic exercise intervention was secured by the design of the two interventions, where the focus of the cognitively demanding exercise intervention was on complex coordination of movements and dealing with changing and increasing task demands, whereas the focus of the aerobic exercise intervention was on highly repetitive and automated exercises with little cognitive demands. Regarding aerobic intensity, we compared the two interventions and control group on the total exposure in MVPA. As intended, the aerobic exercise group was exposed to the highest amount of physical activity and the control group received the lowest exposure to physical activity. These differences indicate that we successfully designed and delivered interventions that differed in terms of the amount of physical activity provided. However, it should be considered that a combination of high-intensity aerobic and high-intensity cognitively demanding exercise is the most effective intervention to increase executive functioning in children. Although the study of Egger et al. (2019) confirmed this for set shifting performance, future research should elucidate whether this also applies for other neurocognitive functions.

Another possible explanation for our finding that neither the aerobic intervention nor cognitively demanding exercise intervention impacted our neurocognitive measures is that our outcome measures may not have been sensitive enough to assess the hypothesized effects. However, in our previous study, we have shown the expected positive associations between cardiovascular fitness and specific aspects of neurocognitive functioning (information processing measures, attention, and visuospatial working memory) using the same set of outcome measures (Meijer et al., 2020). In addition, our measures have shown sensitivity to disorders which are associated with executive functioning impairments (Königs et al., 2015) and for interventions which are aimed at strengthening executive function performance in children (Klingberg, Forssberg, & Westerberg, 2002). Therefore, it seems unlikely that our findings reflect limited sensitivity of our outcome measures to the effects of the interventions studied. It could also be possible that the beneficial effects of cognitively demanding exercise are limited to specific executive functions, which were not included in our neurocognitive assessment. For example, Egger et al. (2019) and Schmidt et al. (2015) found a significant beneficial effect of cognitively demanding exercise on set shifting in particular. Nevertheless, this explanation seems unlikely in the light of many recent reviews and meta-analyses indicating a range of neurocognitive functions to be sensitive to the effects of physical activity (Alvarez-Bueno et al., 2017; Best, 2010; de Greeff et al., 2018; Singh et al., 2018; Verburgh et al., 2014).

Interestingly, analyses aimed at exploring factors that may have influenced intervention effects indicated that children with higher interference control performance at baseline benefited more from the cognitively demanding intervention than children in the control group. One possible account for this unexpected result may be that our cognitively demanding exercise intervention was too challenging for children with lower interference control performance. It may be suggested that there is an optimal complexity of cognitive engagement for the effectiveness of cognitively demanding physical activity (Egger, Conzelmann, & Schmidt, 2018; Pesce et al., 2013). Although both our interventions were designed in collaboration with academic experts and researchers in Human Movement Science and experienced physical education teachers to ensure the cognitive load was age-appropriate, it might be possible that our cognitively demanding exercise was too challenging for some of the lower performing children, as assessed at baseline (see Pesce et al., 2013). This finding may also indicate that children with higher interference performance are better able to suppress irrelevant stimuli in a stimulus-rich environment (i.e., the gym), allowing them to focus more on the cognitively demanding tasks, while children with less well-developed interference control skills would be less able to focus on the cognitively demanding tasks because they may have greater difficulty suppressing irrelevant stimuli. Future studies should take the individual cognitive load into account, for example, using a more controlled environment or smaller exercise groups.

Our study has some important strengths such as the large sample size, the extensive set of neurocognitive function measures, and the use of PCA to cluster neurocognitive variables into more comprehensive neurocognitive component scores. Besides, the current study is one of the few studies that allowed a direct comparison between aerobic exercise and cognitively demanding exercise. Nevertheless, this study also has some limitations. Another limitation of this study is the restricted age range of children studied. Due to the rapid proliferation of executive functioning during the childhood, it is highly possible that the effects of physical activity depend on the child's developmental stage. Furthermore, based on the results of the studies of Egger et al. (2019) and Schmidt et al. (2015) concerning the beneficial effects of cognitively demanding exercise on set shifting, future studies should consider whether to include this measure in their assessments.

In conclusion, the present study showed that 14-week physical exercise interventions involving aerobic activity or cognitively demanding exercise did not benefit executive functioning in school-aged children. However, our results do suggest that exposure to higher levels of MVPA benefits specific aspects of neurocognitive functioning, independent of the type of intervention deployed. This indicates that exposure to MVPA is a crucial aspect of the relationship between physical activity and executive functioning. Given the rapid increase of sedentary behavior among children, our finding is in particularly important for teachers and policy makers. The exposure to aerobic intensity and personalizing cognitive load should be considered crucial aspects of the development and delivery of physical education lessons at primary schools. The inconsistent findings in the literature on the effects of physical activity, as well as the differences between aerobic and cognitively demanding exercise, underline the importance of further research concerning the optimal type, frequency, duration, and intensity of exercise interventions.

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