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Fitness, physical activity, sedentary time, inhibitory control, and neuroelectric activity in children with overweight or obesity: The ActiveBrains project

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Abstract

Whereas numerous studies have investigated the relationship of cardiorespiratory fitness with inhibition and neuroelectric activity, the role of other physical fitness components and physical activity (PA) intensities in this relationship remain unclear, especially in children with obesity. Therefore, the purpose of this study was to investigate the association of physical fitness, PA, and sedentary time with inhibitory control and neuroelectric activity in children. Eighty-four children (8-11 years) with overweight or obesity performed the ALPHA battery to assess their physical fitness components (i.e., muscular strength, speed-agility, and cardiorespiratory fitness). PA and sedentary time were assessed from hip and nondominant wrist-worn accelerometers. Inhibitory control was evaluated using a flanker task, and expressed as reaction time (RT) and response accuracy. P3 amplitude and latency were recorded using electroencephalography. Higher speed-agility and cardiorespiratory fitness were associated with shorter RT and larger P3 amplitude on incongruent trials. Higher speed-agility was associated with shorter RT on congruent trials. Hip-assessed moderate and moderate-to-vigorous PA were associated with longer P3 latency across trials, and vigorous PA with larger P3 amplitude on incongruent trials. Our results provide initial evidence suggesting that not only cardiorespiratory fitness, but also speed-agility, are associated with inhibitory control and P3 amplitude, whereas no significant associations were observed for muscular strength. The associations between PA

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(moderate, vigorous and moderate to-vigorous) and neuroelectric activity were accelerometer location-dependent. Promoting PA programs that enhance the cardiorespiratory fitness and speed-agility will contribute to better understanding whether such health improvements benefit inhibitory control in youth with overweight or obesity.

KEYWORDS

aerobic fitness, cognition, electroencephalography, executive control, ERPs, youth

1 | INTRODUCTION

Childhood obesity has been catalogued as one of the most serious public health problems worldwide (World Health Organization [WHO], 2015). Detrimental effects of childhood obesity may extend beyond metabolic and cardiovascular impairments (Ortega, Lavie, & Blair, 2016) and may impact executive function and brain health (Bauer et al., 2015; Yang, Shields, Guo, & Liu, 2018). Large negative associations have been observed for inhibitory control (Raine et al., 2017; Yang et al., 2018), defined as the ability to suppress the irrelevant information and focus on relevant aspects of the stimulus environment in order to activate the appropriate and correct response schemas. In this context, higher levels of physical fitness and physical activity (PA) may attenuate the harmful effects of obesity on inhibitory control (Ortega, Ruiz, Castillo, & Sjöström, 2008). Given that preadolescent childhood may be a particularly sensitive period for brain development (Giedd et al., 1999) and physical fitness, PA, and sedentary time (Esteban-Cornejo et al., 2017, 2019), it is of great public health importance to investigate the potential protective role of such health factors on brain functioning, especially in children with overweight or obesity.

A recent systematic review in children has evidenced a positive influence of cardiorespiratory fitness on inhibitory control (Donnelly et al., 2016), including studies showing faster (Scudder et al., 2015) and more accurate tasks' responses (Pontifex, Scudder, Drollette, & Hillman, 2012) among individuals with higher cardiorespiratory fitness levels. Findings for PA and sedentary time relative to inhibitory control are less consistent, with positive and null associations reported for both sedentary time (Syväoja, Tammelin, Ahonen, Kankaanpää, & Kantomaa, 2014) and moderate-to-vigorous PA (MVPA) (Pindus et al., 2016, 2019; Syväoja et al., 2014). Beyond the assessment of behavioral outcomes, prior studies have also assessed event-related brain potentials (ERP) (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Pindus et al., 2019; Pontifex et al., 2011; Raine et al., 2018), which provide an understanding of the underlying neuroelectric correlates of cognition that appear modifiable as a function of health factors such as physical fitness, PA, and sedentary time (Hillman, Kamijo, & Pontifex, 2012). In particular, the P3 is a positive-going ERP component whose amplitude is thought to be a neuroelectric correlate of inhibition and proportional to the amount of attentional resources allocated during stimulus engagement, and whose latency is believed to be proportional to the information processing speed (Polich, 2007). Children with higher cardiorespiratory fitness levels have exhibited larger P3 amplitude and shorter P3 latency compared to their lower fit peers during tasks that tap aspects of inhibitory control (Hillman et al., 2009; Pontifex et al., 2011; Raine et al., 2018). In addition, obesity-related deficit in childhood cognitive function has been previously demonstrated with the P3 (Kamijo et al., 2012). Such findings highlight the importance of studying the relationship of fitness and PA with neuroelectric activity, using P3 amplitude and latency as a marker of neuroelectric activity. However, this body of research has not considered the weight status of the children, and has solely focused on cardiorespiratory fitness, with a paucity of evidence for other components of fitness such as speed-agility or muscular strength (Donnelly et al., 2016).

Since the main physical fitness components are differently associated with brain structure (Esteban-Cornejo et al., 2017, 2019), it is interesting to investigate this differential association using measures of brain function, such as neuroelectric activity. In the present study, we took advantage of the excellent temporal resolution of the ERP (i.e., in the range of milliseconds), which offers a comprehensive assessment of aspects of the information processing stream that comprises, for example, inhibitory control. This technique was used to gain insight into the relation of different components of fitness and the temporal dynamics of inhibition (i.e., P3 amplitude and latency). Previous research already suggested a differential association of each fitness component (i.e., cardiorespiratory fitness, speed-agility and muscular strength), not only with the physical health (Ortega et al., 2008; Ruiz et al., 2009), but also with the executive function in children (Donnelly et al., 2016; Mora-Gonzalez et al., 2019a, 2019b). Particularly in children with overweight or obesity, a previous study with the present sample showed that while cardiorespiratory fitness was positively associated with cognitive flexibility, speed-agility was positively related with both cognitive flexibility and inhibitory control, with no associations for muscular strength (Mora-Gonzalez et al., 2019a, 2019b). Studies in children with normal weight that included a measurement of inhibitory control showed that the complex motor skills (e.g., speed-agility) are strongly related to the executive function dimensions such as inhibitory control (van der Fels et al., 2015). Moreover, there is still lack of information with respect to the role of muscular strength in executive function. Thus, it is necessary to disentangle the differential association of the various fitness components with neuroelectric activity during inhibitory control operations in children with overweight or obesity.

With respect to PA, only one study has investigated the associations of objectively measured PA, using an accelerometer located on the waist, with P3 amplitude and latency during an inhibitory control task (Pindus et al., 2019). In that study, neither moderate nor vigorous PA were related to reaction time and response accuracy during an inhibitory control task (Pindus et al., 2019). Further, no association was observed for P3 amplitude, whereas bouted vigorous PA predicted shorter P3 latency across flanker conditions. However, this study sampled a combination of children with normal weight with a small proportion of children with overweight or obesity, which limited the possibility of drawing conclusions for children with overweight or obesity as a risk group for cognitive impairments (Yang et al., 2018). There is currently scarce information about the relation of other health behaviors, particularly as assessed with objective methods, to neuroelectric and cognitive outcomes in obese individuals, including time in sedentary behaviors and time in light PA. In this context, one of the decisions that needs to be made when using accelerometry as an objective method to assess PA and sedentary time is accelerometer placement (Migueles et al., 2017). To date, no conclusive information is yet available with respect to which accelerometer placement is more valid and reliable in children (Migueles et al., 2017), and as a consequence, in the present study we included data from both hip and wrist accelerometer locations.

Finally, the study of the relationship between sedentary time and neuroelectric activity during an inhibitory control task is relatively novel. It is important to differentiate between physical inactivity (i.e., the level of activity in which the PA Guidelines are not met) (Physical Activity Guidelines Advisory Committee, 2018) and sedentary behavior (i.e., any waking behavior with an energy expenditure ≤1.5 metabolic equivalents while in a sitting or reclining position) (Tremblay et al., 2017). Whereas several studies have largely suggested that, sedentariness (e.g., screen time) is negatively related with children's executive function (Johnson, Cohen, Kasen, & Brook, 2007; Landhuis, Poulton, Welch, & Hancox, 2007), to the best of our knowledge, there are no previous studies addressing the relationship between sedentary time and inhibitory control in children with overweight or obesity.

Accordingly, the aim of this study was to investigate the association of different physical fitness components (i.e., muscular strength, speed-agility, and cardiorespiratory fitness), various PA intensities, and sedentary time on behavioral and neuroelectric (i.e., P3 amplitude and latency) concomitants of inhibitory control in children with overweight or obesity. We hypothesized that higher levels of physical fitness, and particularly of cardiorespiratory fitness and speed-agility, would be associated to higher inhibitory control performance and underlying neuroelectric activity (i.e., larger P3 amplitude and shorter P3 latency). In particular, we expected this relationship to be stronger for the task's condition requiring higher demands of inhibitory control (Pontifex et al., 2011). With respect to the relationship of the different PA intensities and sedentary time with inhibitory control and neuroelectric activity, we were uncertain since these relationships have shown to be more inconsistent (Donnelly et al., 2016). We hypothesized that vigorous PA would be associated with shorter P3 latency based on one prior study in children (Pindus et al., 2019).

2 | METHOD

2.1 | Participants

This cross-sectional study was conducted under the umbrella of the ActiveBrains project (http://profith.ugr.es/activebrains) (Cadenas-Sánchez et al., 2016). The complete methodology, procedures and inclusion/exclusion criteria for participating in the project have been previously described (Cadenas-Sánchez et al., 2016). An initial sample of 110 children aged 8–11 years with overweight or obesity were recruited from Granada, Spain. The present study used baseline data prior to randomization, collected from November 2014 to February 2016 in three different waves. A final sample of 84 Caucasian children (10.1 ± 1.1 years old; 56% boys) with complete baseline data on selected outcomes was included in the present analysis. Description and characteristics of the study were given to parents or legal guardians, and a written informed consent was provided from both guardian and child. The ActiveBrains project was approved by the Ethics Committee on Human Research of the University of Granada, and was registered in ClinicalTrials.gov (identifier: NCT02295072).

2.2 | Physical fitness components

The ALPHA health-related physical fitness test battery for children and adolescents was used to assess the physical fitness components (i.e., muscular strength, speed-agility and cardiorespiratory fitness). A detailed description of the validity and reliability of the ALPHA battery has been provided elsewhere (Ruiz et al., 2011). Upper limb strength was assessed by the maximum handgrip strength test (TKK 5101 Grip D, Takei, Tokyo, Japan). This test was performed twice, and the maximum score of each hand was obtained and averaged as an absolute measurement of upper limb strength (kg). Lower limb strength was assessed using the standing long jump test. This test was performed three times and the longest jump was recorded in centimeters (cm) as a relative measurement of lower limb strength. For exploratory analyses, we also computed an absolute strength measurement of lower limbs (cm * body weight). Speed-agility was assessed using the 4 × 10-m shuttle-run test (4 × 10m SRT). The test was performed twice and the fastest time was recorded in seconds. Since a longer completion time indicates poorer performance (i.e., slower and less agile) and for analysis purposes, we inverted this variable by multiplying test completion time (s) by −1, so that higher scores indicated greater speed-agility levels. Cardiorespiratory fitness was assessed via a 20-m shuttle-run test (20 m SRT). This test was performed once and always at the end of the fitness battery testing session. The total number of completed laps was registered.

2.3 | Physical activity and sedentary time

PA and sedentary time were assessed with accelerometers (GT3X+, ActiGraph, Pensacola, FL, USA). Children simultaneously wore two accelerometers located on the right hip and non-dominant wrist during 7 consecutive days (24 hr/day). Participants were instructed to remove the accelerometers only for water activities (i.e., bathing or swimming). Raw data collected at a sampling frequency of 100 Hz were loaded in ActiLife (ActiGraph, Pensacola, FL, USA) and processed afterwards in R (v. 3.1.2, https://www.cran.r-project.org/) using the GGIR package (v. 1.6–0, https://cran.r-project.org/web/packages/GGIR/) (van Hees et al., 2013). We calculated the Euclidean Norm Minus One G metric (ENMO, 1 $G \sim 9.8$ m/s^2) using data from three axes of the accelerometer after auto-calibrating the acceleration signal (van Hees et al., 2013, 2014). The mean of ENMO with negative values rounded to zero was calculated over 5s epochs. Accelerometric information processing in GGIR consisted in: (a) Non-wear time detection (van Hees et al., 2011); (b) Detection of abnormally and sustained high acceleration values (i.e., clipped time); (c) Replacement of the non-wear and clipped time by the mean acceleration recorded within the same time frame for the rest of the measurement (van Hees et al., 2011). A replacement by 0 for all metrics was performed if no data were collected for a specific time frame for the rest of the days; (d) Identification of waking and sleeping hours based on an automatized algorithm guided by the diaries completed by the participants (van Hees et al., 2015). The inclusion criterion for a valid day was wearing the accelerometer with ≥16 hr/day. Data from the entire 24-hr period for each day was used, and a minimum of 4 valid days (3 weekdays and 1 weekend day) per week was required to be included in the analyses. The compliance wearing the accelerometer was high, with 98% of the sample wearing the accelerometers for ≥6 days. PA and sedentary time were classified into different intensities following hip- and nondominant wrist-based cut-off points for the ENMO metric (Hildebrand, Hansen, van Hees, & Ekelund, 2016; Hildebrand, Van Hees, Hansen, & Ekelund, 2014). For the present study, the data are presented from the hip- and wrist-mounted accelerometer. For informative purposes, when using data from hip, only 8% of the children met the PA guidelines (i.e., ≥60 min/d of MVPA), and when using data from nondominant wrist, 27% of the children met the PA guidelines. Since no information is yet available with respect to which accelerometer placement is more valid and reliable in children (Migueles et al., 2017), and given the importance of accelerometer placement when assessing PA and sedentary time, we included the assessment of these variables from both hip and nondominant wrist accelerometer locations. Main analyses were performed using data from the hip to allow possible comparisons with previous studies (Pindus et al., 2019; Syväoja et al., 2014), but analyses were replicated using data from nondominant wrist. The variables included in this study were total minutes per day of light PA, moderate PA, vigorous PA, MVPA, and sedentary time.

2.4 | Inhibitory control

All participants completed a modified picture-based version of the Eriksen flanker task to assess the inhibitory control (Eriksen & Eriksen, 1974). Trials from this task consisted of five cows that were focally presented (1.2° visual angle) on a computer screen using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Participants were instructed to respond as quickly and accurately as possible with their dominant hand using an index finger press on a mouse to the direction (i.e., right or left) of the centrally presented target (i.e., 1.2-cm tall cow on a blue background). First, they were instructed to focus on a fixation point ("+") presented for an average time of 1,250 ms (randomly ranging from 833 to 2,160 ms) in the center of the screen. Next, the fixation point disappeared and the target was presented with a response window up to 1,700 ms. Participants were instructed to focus on the middle cow appearing in the same place where the fixation point had been presented. After the target, a feedback message ("Congrats, this is correct!"; "Incorrect, keep it trying!") was displayed for 1,000 ms. Feedback was used to maintain motivation and attention as in previous studies (Lewis, Reeve, & Johnson, 2018; Richardson, Anderson, Reid, & Fox, 2018). The inter-trial interval (ITI) ranged from 3,682 to 6,158 ms (average ITI = 4,875 ms). There were two different trials, congruent and incongruent, depending on the directions of the flanking nontarget stimuli (i.e., four identical cows) (Figure 1). Thus, for congruent trials, both the target and flanking stimuli were positioned in the same

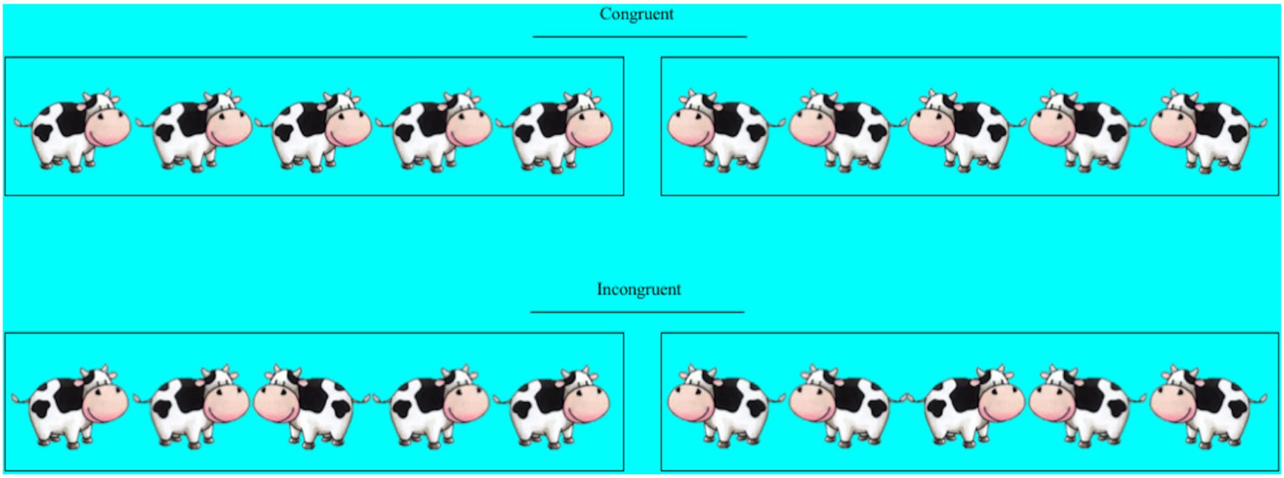

FIGURE 1 Congruent and incongruent trials from the picture-based version of the Eriksen flanker task

direction, either right or left. For incongruent trials, the target and flanker stimuli were positioned in opposite directions from each other, thus requiring the upregulation of inhibitory control to gate out perceptual interference and response schemas associated with the direction of the flanking stimuli. Participants were given a practice block consisting of 12 trials. If they failed to perform the task to proceed with the experimental block, we repeated the instructions and made sure that they understood them. Subsequently, a total of 144 experimental trials were presented randomly in three blocks of 48 trials each, with equal probability of appearance for congruent and incongruent trials. Measures of mean RT (s) and response accuracy (%) were collected over the correct trials.

2.5 | Neuroelectric activity

Neuroelectric activity was recorded from 64 electrode sites arranged in an extended montage based on the International 10–10 system (Chatrian, Lettich, & Nelson, 1985) using the ActiveTwo System of BioSemi (24-bit resolution, biopotential measurement system with Active Electrodes; Biosemi, Amsterdam, Netherlands). Data were digitized at a rate of 1,024 Hz and a 100-Hz low-pass filter. Information regarding EEG data processing is provided in Supplementary Figure S1. After processing, behavioral data were merged with EEG data and stimulus-locked epochs were created from a window of −199.0 prior to 1,700 ms after stimulus onset and baseline corrected using the −100 to 0 ms pre-stimulus period. The P3 component was evaluated within each of the 64 electrode sites as the mean amplitude within a 50 ms interval surrounding the largest positive going peak within a 300 to 700 ms latency window following onset of the target stimulus. P3 latency was defined as the time point corresponding to the maximum P3 peak amplitude during this same latency window. Data for both amplitude and latency were then averaged across a 9-electrode site region of interest over the parietal and occipital regions (P1/Z/2, PO3/Z/4, O1/Z/2). This region of interest was selected as it corresponded to the topographic maxima of the P3 ERP component elicited in response to the picture-based flanker task used in the present investigation. However, other studies also analyzing the relationship between physical fitness, PA, and inhibitory control measured via a flanker task presented a different region of interest, such as over the centro-parietal region corresponding to where the P3 has its maximum (Raine et al., 2018), or the activity in the midline electrodes (Hillman et al., 2009; Pontifex et al., 2011).

2.6 | Potential confounders

Potential confounding variables selected for analyses were sex, peak height velocity (PHV; an indicator of maturity during childhood and adolescence computed from age and anthropometric variables following Moore's equations) (Moore et al., 2015), body mass index (BMI; kg/m^2), recruitment wave (i.e., 1, 2, or 3), self-reported parental educational level (i.e., neither had a university degree; one had a university degree; or both had a university degree), and intelligence quotient (IQ) assessed by the Spanish version of the Kaufman Brief Intelligence Test (K-BIT) (Kaufman & Kaufman, 1990). The selection of the confounders was performed based on prior research (Donnelly et al., 2016) and exploratory analyses performed with other potential confounders not included in the present study (e.g., chronological age).

2.7 | Statistical analysis

The characteristics of the study sample are presented as means and standard deviations (*SD*) or percentages. After checking for normal distribution, response accuracy from both the congruent and incongruent trials was normalized using Blom formula (Malina, Rogol, Cumming, Coelho e Silva, & Figueiredo, 2015) because it showed skewed distribution. Interaction analyses were performed between sex and physical fitness, PA and sedentary time on the outcomes. No significant interactions between sex and the predictors on the outcomes were found ($p > .10$), hence analyses were performed for the whole sample. Bivariate Pearson correlations were performed to test the associations between potential confounders and inhibitory control and neuroelectric outcomes. A statistical summary of these correlations is provided in Supplementary Table S1.

To examine the associations of physical fitness, PA and sedentary time with inhibitory control performance (i.e., RT and response accuracy) and neuroelectric activity (i.e., P3 amplitude and P3 latency), linear hierarchical regression analyses were performed. Potential confounders (i.e., sex, PHV, BMI, wave, parental educational level, and IQ) were included into step 1 of a stepwise method to test their association to the outcomes and, subsequently, each physical fitness, PA and sedentary time variable was entered individually into step 2, in separate regression analyses. The R squared changes obtained from the regressions are represented graphically. In addition, we computed the median split for physical fitness, PA and sedentary time variables to visually represent their relation with P3 amplitude and latency. An exploratory analysis was performed to test the associations when lower limb strength was expressed in absolute terms, and also to test the independent associations of physical fitness components with inhibitory control and neuroelectric activity. Another exploratory analysis was performed to test whether the associations between PA and neuroelectric activity remained significant after adjustment for cardiorespiratory fitness. We corrected for multiple comparisons by defining statistical significance as a Benjamini–Hochberg false discovery rate $q < 0.05$ (Benjamini & Hochberg, 1995). All the statistical procedures were performed using SPSS software for Mac (version 22.0, IBM Corporation).

3 | RESULTS

The descriptive characteristics for the study sample are presented in Table 1.

No associations were observed for muscular strength variables with any of the behavioral (Table 2) or neuroelectric (Table 3, Figure 2) outcomes (p's > .05). Higher speed-agility was associated with shorter RT in both the congruent ($\beta = -0.276$) and incongruent ($\beta = -0.305$) conditions (p's $\leq .009$) (Table 2). Higher speed-agility was also associated with larger P3 amplitude only for incongruent trials ($\beta = 0.299$, $p < .01$) (Table 3, Figure 2). Higher cardiorespiratory fitness was associated with shorter RT ($\beta = -0.278$, $p = .01$) (Table 2) and larger P3 amplitude, only for incongruent trials ($\beta = 0.303$, $p < .01$) (Table 3, Figure 2). In the exploratory analyses using a model mutually adjusted for speed-agility and cardiorespiratory fitness, none of the previous associations remained significant ($p > .05$; data not shown).

No associations were observed for light PA, and sedentary time with any of the behavioral (Table 2) or neuroelectric (Table 3, Figure 3), outcomes (p's > .05), regardless of the location of the accelerometer (Supplementary Tables S2 and Table S3). Higher moderate PA and MVPA were associated with longer P3 latency in both the congruent and incongruent trials (β ranging from 0.309 to 0.327, all $p \leq .004$), only for hip-worn PA data (Table 3, Figure 3), and these associations remained significant following the adjustment for cardiorespiratory fitness (β ranging from 0.363 to 0.401, all $p \leq .001$; data not shown). Higher vigorous PA was associated with larger P3 amplitude in the incongruent condition ($\beta = 0.274$, $p = .010$), only for hip-worn PA data (Table 3, Figure 3), although this association did not remain significant after adjustment for cardiorespiratory fitness ($\beta = 0.166$, $p = .156$; data not shown). Finally, Figure 4 depicts the R squared changes from the regression of each physical fitness component, PA intensity and sedentary time with P3 amplitude.

4 | DISCUSSION

The findings of the present study replicate prior research with cardiorespiratory fitness, and extended the field by revealing a relation of speed-agility with behavioral and neuroelectric outcomes of inhibitory control, although these associations were not independent of one another. Such an association was not observed for muscular strength, suggesting selectivity in the relation of the various components of fitness with cognition in children with overweight or obesity. In addition, sedentary time was not associated with inhibitory control outcomes, whereas associations for PA were observed using hip-worn accelerometer data. Collectively our data suggest that speed-agility and cardiorespiratory fitness both individually, but not muscular strength, are related to inhibitory control and underlying brain activity in children with overweight or obesity. The relations observed between PA intensities and neuroelectric activity must be interpreted with caution due to the inconsistency observed across accelerometer placements.

The present study shows that higher speed-agility and cardiorespiratory fitness were associated with better inhibitory control during a modified flanker task. The associations observed for speed-agility are consonant with previous findings showing a relation between other complex motor skills (e.g., jumping, sprinting, coordinating) and inhibitory control in children with normal weight (Aadland et al., 2017). With regards to the cardiorespiratory fitness, the findings of the

TABLE 1 Descriptive characteristics of the study sample

	All (n = 84)	Boys (n = 47)	Girls (n = 37)
Sociodemographic characteristics			
Age (years)	10.1 ± 1.1	10.2 ± 1.1	9.9 ± 1.1
Peak height velocity (years)	–2.2 ± 1.0	–2.6 ± 0.7	–1.7 ± 1.0
Weight (kg)	56.1 ± 10.4	56.5 ± 10.0	55.7 ± 11.0
Height (cm)	144.3 ± 8.0	144.9 ± 7.0	143.7 ± 9.1
Body mass index (kg/m^2)	26.8 ± 3.5	26.8 ± 3.7	26.8 ± 3.4
Intelligence quotient (total score)	99.3 ± 11.7	98.1 ± 11.3	100.8 ± 12.2
Wave of participation 1/2/3 (%)	17.9/36.9/45.2	12.8/44.7/42.6	24.3/27.0/48.6
Parental university level (%)			
None of them	66.7	72.3	59.5
One of them	16.7	12.8	21.6
Both of them	16.7	14.9	18.9
Physical fitness components			
Upper limb absolute strength (kg)	16.7 ± 3.6	17.5 ± 3.8	15.7 ± 3.1
Lower limb relative strength (cm)	106.2 ± 18.3	109.5 ± 16.4	102.1 ± 19.9
Speed-agility (s)[a]	15.0 ± 1.5	14.6 ± 1.5	15.5 ± 1.5
Cardiorespiratory fitness (laps)	16.1 ± 7.8	17.7 ± 7.9	14.2 ± 7.2
PA and sedentary time (min/day)[b]			
Light PA	64.9 ± 15.4	66.4 ± 15.0	62.9 ± 15.9
Moderate PA	32.6 ± 13.5	37.2 ± 14.6	26.7 ± 9.2
Vigorous PA	3.0 ± 2.0	3.7 ± 2.1	2.1 ± 1.4
MVPA	35.6 ± 14.9	40.9 ± 16.0	28.9 ± 10.0
Sedentary time	810.0 ± 59.5	799.2 ± 62.1	823.8 ± 53.6
Inhibitory control task			
Congruent			
Mean reaction time (ms)[a]	801.3 ± 119.5	801.6 ± 130.2	800.9 ± 106.2
Response accuracy (%)	94.5 ± 5.8	95.2 ± 4.9	93.5 ± 6.7
Incongruent			
Mean reaction time (ms)[a]	845.7 ± 132.2	844.2 ± 137.8	847.7 ± 126.7
Response accuracy (%)	90.5 ± 10.9	89.8 ± 12.3	91.5 ± 8.7
Neuroelectric measurements			
Congruent			
P3 amplitude (µV)	9.2 ± 4.5	9.2 ± 4.2	9.2 ± 4.9
P3 latency (ms)[a]	433.4 ± 52.1	441.1 ± 54.8	423.6 ± 47.3
Incongruent			
P3 amplitude (µV)	9.3 ± 4.7	9.6 ± 4.4	8.8 ± 5.1
P3 latency (ms)[a]	436.3 ± 53.0	441.7 ± 51.7	429.4 ± 54.6

Notes: Values are expressed as mean ± *SD*, unless otherwise indicated. Upper limb absolute strength was measured by the handgrip strength test. Lower limb relative strength was measured by the standing long jump test. Speed-agility was measured by the 4 × 10-m shuttle run test. Cardiorespiratory fitness was measured by a 20-m shuttle run test (20 m SRT). Mean ± *SD*s values for neuroelectric measurements reflect the mean amplitude across a 9-electrode site region of interest (P1/Z/2, PO3/Z/4, O1/Z/2).

Abbreviations: MVPA, moderate-to-vigorous physical activity; PA, physical activity.

[a]Lower values indicate better performance.

[b]PA and sedentary time variables were obtained from the hip.

TABLE 2 Hierarchical regressions for the association of physical fitness, physical activity (PA), and sedentary time (hip) with inhibitory control for congruent and incongruent trials ($n = 84$)

	Congruent (lower cognitive demand)								Incongruent (higher cognitive demand)							
	Mean reaction time (ms)				Response accuracy (%)[b]				Mean reaction time (ms)				Response accuracy (%)[b]			
	R^2	R^2 change	β	p	R^2	R^2 change	β	p	R^2	R^2 change	β	p	R^2	R^2 change	β	p
Physical fitness																
Upper limb absolute strength (kg)	0.120	0.014	–0.128	.271	0.256	0.003	–0.076	.560	0.024	0.024	–0.155	.160	0.232	0.003	0.057	.612
Lower limb relative strength (cm)	0.145	0.038	–0.199	.064	0.255	0.002	–0.053	.660	0.066	0.066	–0.256	.019	0.230	0.000	0.015	.895
Speed-agility (s)[a]	0.180	0.073	–0.276	**.009**	0.288	0.035	0.255	.053	0.093	0.093	–0.305	**.005**	0.242	0.012	0.131	.266
Cardiorespiratory fitness (laps)	0.155	0.048	–0.223	.036	0.254	0.001	0.039	.772	0.077	0.077	–0.278	**.010**	0.258	0.029	0.208	.086
PA and sedentary time (min/day)																
Light PA	0.107	0.000	0.003	.979	0.291	0.039	–0.204	.043	0.008	0.008	0.091	.410	0.244	0.014	–0.125	.226
Moderate PA	0.112	0.005	0.077	.484	0.270	0.017	–0.146	.183	0.038	0.038	0.194	.076	0.238	0.009	–0.101	.344
Vigorous PA	0.120	0.013	–0.117	.279	0.253	0.001	0.029	.801	0.004	0.004	–0.059	.592	0.231	0.002	–0.043	.691
MVPA	0.110	0.003	0.054	.623	0.266	0.014	–0.133	.233	0.028	0.028	0.169	.125	0.238	0.008	–0.098	.360
Sedentary time	0.108	0.001	–0.033	.758	0.257	0.004	0.067	.528	0.009	0.009	–0.094	.396	0.230	0.001	0.035	.758

Notes: Each physical fitness and PA/sedentary time variable was introduced in individual hierarchical regression models. Bold font is used to highlight significant associations after adjustment for multiple comparisons using the Benjamini and Hochberg method ($q < 0.05$). Potential confounders (i.e., sex, peak height velocity, body mass index, wave of participation, parental educational level and intelligence quotient) were included into step 1 of the stepwise regression to test their association to the outcomes. Hierarchical regression models for physical fitness, PA and sedentary time with congruent condition parameters: for mean reaction time, peak height velocity, and intelligence quotient were included as confounders; for response accuracy, sex, peak height velocity, body mass index, and intelligence quotient were included as confounders. Hierarchical regression models for physical fitness, PA and sedentary time with incongruent trial parameters: for mean reaction time, no confounders were included; for response accuracy, peak height velocity, wave, body mass index, and intelligence quotient were included as confounders. β values are standardized regression coefficients.

Abbreviation: MVPA, Moderate-to-vigorous physical activity.

[a]This variable was inverted so that higher values indicate better performance.

[b]Normalized values were used in the analysis.

TABLE 3 Hierarchical regressions for the association of physical fitness, physical activity (PA), and sedentary time (hip) with P3 amplitude and latency for congruent and incongruent trials ($n = 84$)

	Congruent (lower cognitive demand)				Incongruent (higher cognitive demand)			
	R^2	R^2 change	β	p	R^2	R^2 change	β	p
P3 amplitude								
Physical fitness								
Upper limb absolute strength (kg)	0.060	0.014	–0.123	.270	0.065	0.002	–0.051	.649
Lower limb relative strength (cm)	0.056	0.010	0.098	.367	0.125	0.062	0.249	.019
Speed-agility (s)[a]	0.076	0.030	0.175	.106	0.151	0.088	0.299	**.005**
Cardiorespiratory fitness (laps)	0.074	0.028	0.169	.119	0.154	0.092	0.303	**.004**
PA and sedentary time (min/day)								
Light PA	0.063	0.017	0.129	.235	0.067	0.004	0.065	.547
Moderate PA	0.046	0.000	0.000	.996	0.063	0.001	0.026	.808
Vigorous PA	0.083	0.037	0.195	.073	0.137	0.074	0.274	**.010**
MVPA	0.047	0.001	0.025	.820	0.066	0.004	0.059	.582
Sedentary time	0.048	0.002	–0.046	.675	0.081	0.019	–0.138	.201
P3 latency								
Physical fitness								
Upper limb absolute strength (kg)	0.013	0.013	0.116	.294	0.007	0.007	0.082	.459
Lower limb relative strength (cm)	0.000	0.000	–0.006	.954	0.010	0.010	–0.098	.376
Speed-agility (s)[a]	0.004	0.004	–0.064	.560	0.017	0.017	–0.131	.236
Cardiorespiratory fitness (laps)	0.008	0.008	–0.089	.421	0.041	0.041	–0.202	.066
PA and sedentary time (min/day)								
Light PA	0.009	0.009	0.095	.389	0.015	0.015	0.122	.268
Moderate PA	0.105	0.105	0.325	**.003**	0.107	0.107	0.327	**.002**
Vigorous PA	0.013	0.013	0.112	.310	0.014	0.014	0.120	.278
MVPA	0.096	0.096	0.309	**.004**	0.098	0.098	0.312	**.004**
Sedentary time	0.051	0.051	–0.226	.038	0.015	0.015	–0.122	.269

Notes: Each predictor variable was introduced in individual hierarchical regression models. Bold font is used to highlight significant associations after adjustment for multiple comparisons using the Benjamini and Hochberg method ($q < 0.05$). Potential confounders (i.e., sex, peak height velocity, body mass index, wave of participation, parental educational level, and intelligence quotient) were included into step 1 of the stepwise regression to test their association to the outcomes. Hierarchical regression models for physical fitness, PA and sedentary time with P3 amplitude in both the congruent and incongruent trials were adjusted by intelligence quotient. Hierarchical regression models for physical fitness, PA, and sedentary time with P3 latency in both the congruent and incongruent trials were not adjusted by any confounders. β values are standardized regression coefficients.

Abbreviation: MVPA, Moderate-to-vigorous physical activity.

[a]This variable was inverted so that higher values indicate better performance. P3 amplitude and latency were computed from parieto-occipital region electrodes (i.e., P1, PZ, P2, PO3, POz, PO4, O1, Oz, O2).

present study are in accordance with those of the only study including children with overweight or obesity and a flanker task (Scudder et al., 2015). In that study, higher cardiorespiratory fitness was associated with shorter mean RT (Scudder et al., 2015). Other investigations in children with normal weight reported similar results (Scudder et al., 2014; Westfall, Kao, Scudder, Pontifex, & Hillman, 2017). Although our findings regarding fitness and inhibitory control performance were observed for mean RT, with no associations observed for response accuracy, the majority of previous research found a fitness-related association with accuracy rather than with response speed in child populations (Hillman et al., 2009; Pontifex et al., 2011; Raine et al., 2018). These findings may occur because children have a bias toward speeded responses, that is, children may trade accuracy for speed. As commented previously, other studies also found a relationship of fitness with RT (Scudder et al., 2014, 2015; Westfall et al., 2017) and therefore we could conclude that, taking all

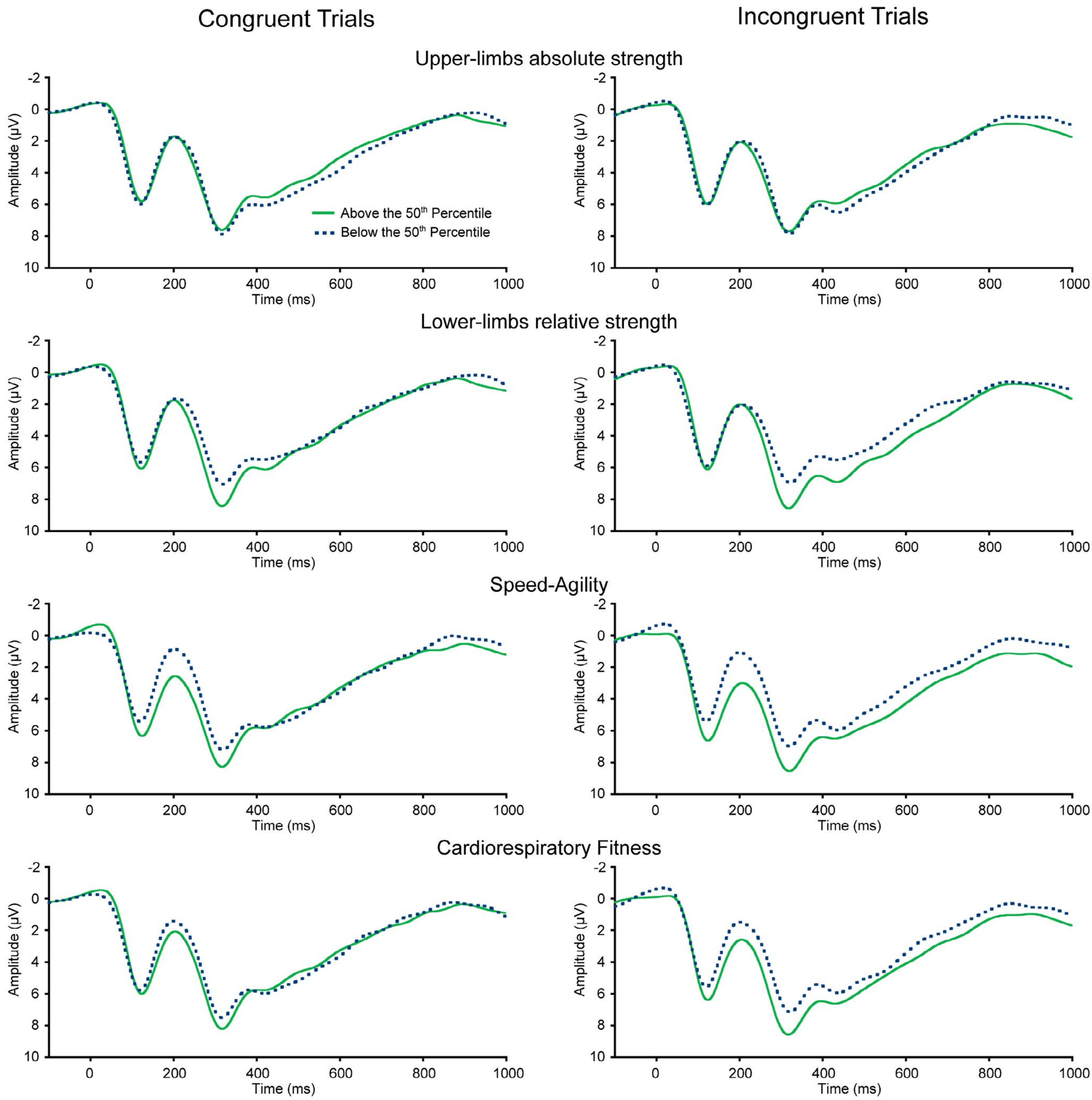

FIGURE 2 Median split waveforms time-locked to the onset of the choice stimulus for each component of physical fitness

existing evidence together (including our present findings), fitness is linked to better inhibitory control performance from a global perspective (i.e., either speed or accuracy) across the majority of studies using flanker tasks.

Previous studies have focused on children with normal weight when studying the relation between physical fitness and neuroelectric activity (Hillman et al., 2009; Pontifex et al., 2011; Raine et al., 2018). Overall, the findings of the present study support this body of research with cardiorespiratory fitness showing that higher fit children exhibited larger P3 amplitude than their lower fit peers during a flanker task (Hillman et al., 2009; Pontifex et al., 2011; Raine et al., 2018). Further, the nonassociation observed between cardiorespiratory fitness and P3 latency concurs with a recent study also showing null association for P3 latency in children (Raine et al., 2018). No associations were observed for any of the muscular strength indicators with inhibitory control performance and neuroelectric activity. In children, a single study including a measurement of overall muscular strength found a positive association between muscular strength and working memory (Kao, Westfall, Parks, Pontifex, & Hillman, 2016). However, to the best of our knowledge, there is no evidence concerning muscular strength and inhibitory control in children, which

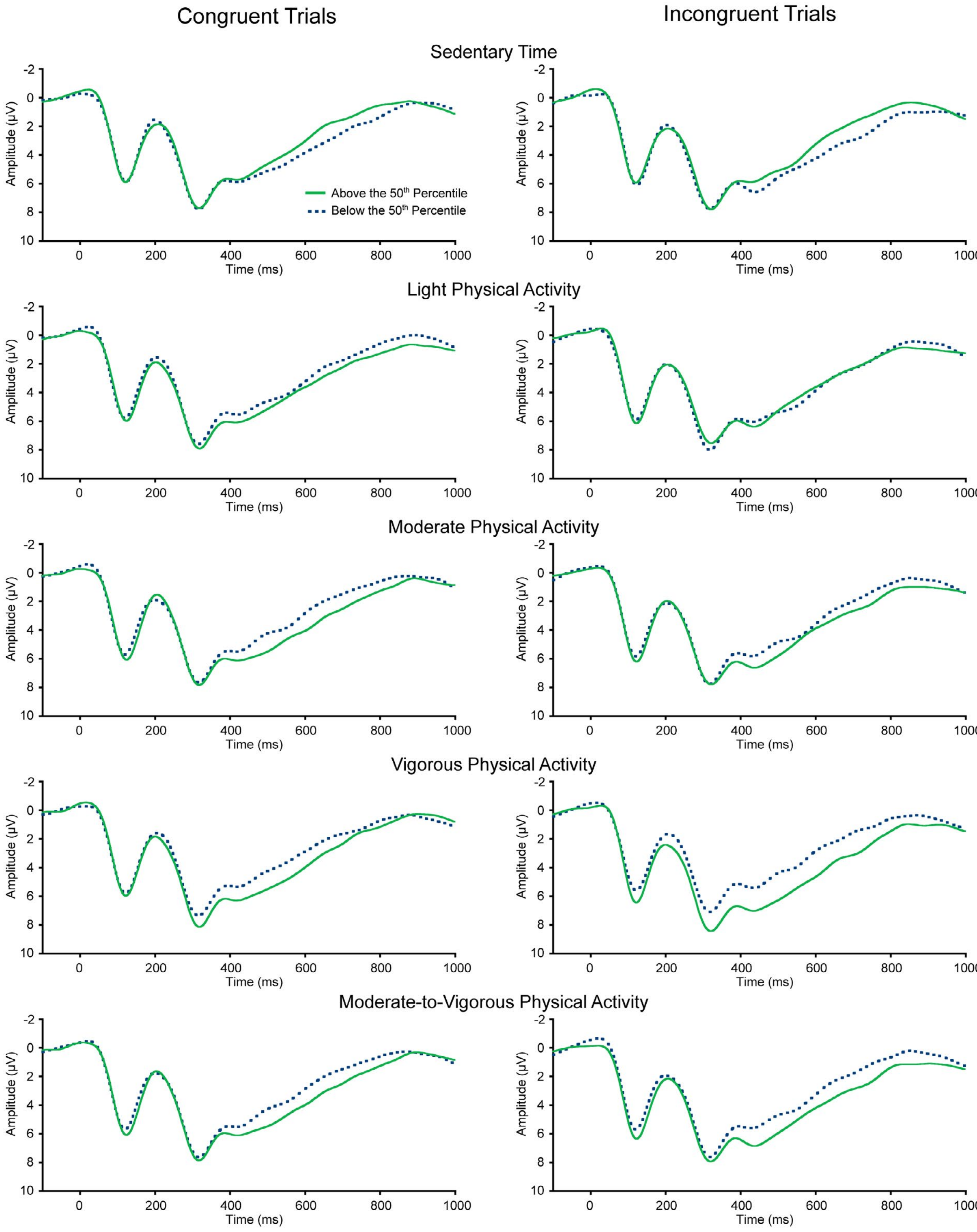

FIGURE 3 Median split waveforms time-locked to the onset of the choice stimulus for each physical activity and sedentary time outcome

hampers comparisons with other studies. Furthermore, the lack of associations found for muscular strength, inhibitory control, and underlying neuroelectric activity occurred in a sample of children with overweight or obesity, which is hardly extrapolated to children with normal weight. Collectively, the associations found in the present study were generally observed in the incongruent condition, indicating that higher fit children were more effective in allocating attentional resources and that the fitness (i.e., cardiorespiratory fitness and speed-agility) relation may be selective for flanker conditions that engender greater amounts of inhibitory control, as has been previously

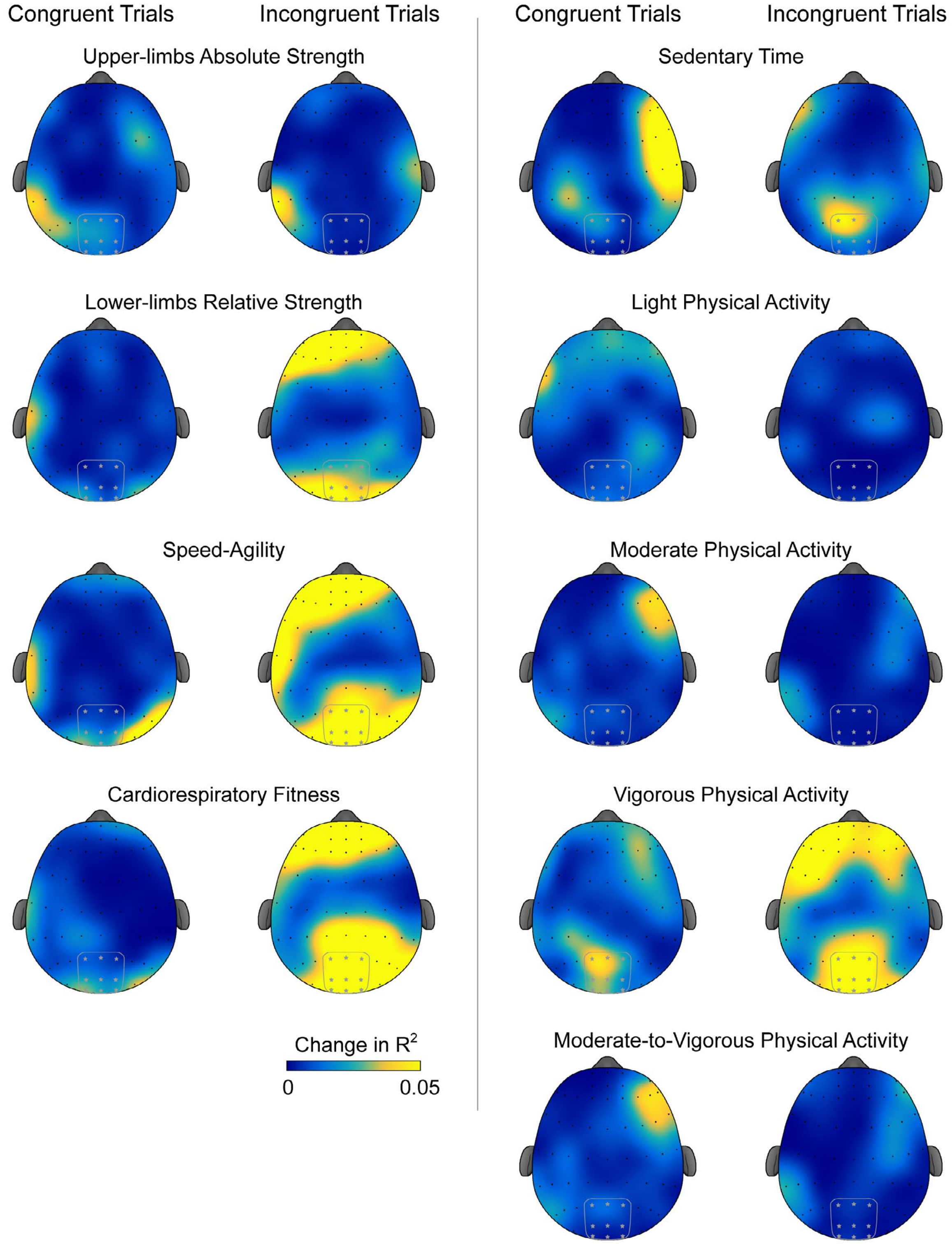

FIGURE 4 Topographic plots of the associations between physical fitness components, physical activity intensities and sedentary time, and P3 amplitude. The 9-electrode site parieto-occipital region of interest that was utilized for analyses is indicated by the bounding box

reported (Pontifex et al., 2011). However, the associations found for speed-agility and cardiorespiratory fitness in the present study were not independent of one another. This might be explained by the fact that the correlation between both variables is very high ($r = .8$, $p < .001$) and, therefore, those children who possess higher cardiorespiratory fitness are typically faster and more agile, and vice versa. Further experimental research should study the independent effect of each other.

Overall, observational studies in children covering the relation of PA and sedentary time with inhibition have reported inconsistent findings (Pindus et al., 2016, 2019; Syväoja et al., 2014). For example, a prior study including children from across weight continuum found seemingly different results in that higher MVPA was associated with shorter RT during a task involving attention but children who spent more time being sedentary achieved better scores on a sustained attention test (Syväoja et al., 2014). In contrast, two recent studies that also included children from across the weight continuum and used a modified flanker task, found no associations of PA estimates with either mean RT or response accuracy in any of the task conditions (Pindus et al., 2016, 2019). An explanation for the null associations between PA and inhibitory control in our study might be the fact that PA was measured only during one week and the PA behavioral pattern of the participants during that week may not be representative of their total PA. Despite the controversial findings, emergent evidence from randomized controlled trials have suggested a positive effect of PA interventions on executive function in children (Donnelly et al., 2016; Hillman et al., 2014; Physical Activity Guidelines Advisory Committee, 2018). Further research is needed in relation to studying different PA intensities and its relationship to inhibitory control and neuroelectric activity in children, specifically in the context of obesity. Such an argument is supported by the findings in children with normal-weight referring to the effects of spending time in the target heart zone during a PA program on inhibitory control, as measured via a Stroop test (Castelli, Hillman, Hirsch, Hirsch, & Drollette, 2011), as well as by the emergent benefits of high intensity interval training on the performance in tasks measuring inhibitory control (Moreau, Kirk, & Waldie, 2017).

Importantly, only one study previously investigated ERPs to gain a better understanding of the role of PA on underlying processes of inhibitory control (Pindus et al., 2019). In that study, although a significant pattern was only found for the relation between bouts of vigorous PA and P3 latency, this association disappeared upon correction for multiple comparisons. Similarly, main analysis from the present study found that higher amounts of vigorous PA were associated with larger P3 amplitude, although this association did not remain significant after adjustment for cardiorespiratory fitness. This finding suggests that the vigorous PA association with P3 amplitude reflects the cardiorespiratory fitness relationship with P3 amplitude that has been shown previously in the literature (Hillman et al., 2009; Pontifex et al., 2011; Raine et al., 2018). Also, it provides further support for previous findings reporting a lack of a relationship between PA and P3 amplitude (Pindus et al., 2019). Higher moderate PA and MVPA were associated with longer P3 latency (i.e., children with higher levels of moderate PA and MVPA demonstrated slower cognitive processing speed). Findings for vigorous PA, moderate PA and MVPA were obtained only when using PA data from the hip accelerometer-location, but not with the wrist-based monitor, and should therefore be considered with caution due to the inconsistency observed across accelerometer placements. Thus, a possible reason behind this accelerometer-location differences observed in the present study may be that hip and wrist-based data are not directly comparable. This is because the movement pattern of certain activities is completely different when measured from hip or wrist (Arvidsson et al., 2019). More concretely, a recent study affirmed that the human's biomechanical model is mainly applicable to explain PA intensities from hip- and thigh-based accelerometer recordings, whereas the wrist itself has a more variable movement pattern not always related to the movement intensity of the rest of the body (Arvidsson et al., 2019). Therefore, the large variability of PA and sedentary time estimates may be a consequence of the lack of standardization in accelerometry data collection (e.g., several device placements) and reduction protocols (e.g., intensity thresholds) (Kerr et al., 2017; Migueles et al., 2019). In fact, differences between findings of our study and the study of Pindus et al., (2019) may be due to the different analytical approaches used when analyzing PA data. To enhance comparability, future studies should also include cut-points free metrics to assess the relationship of PA and neurocognitive outcomes (Migueles et al., 2019; Rowlands et al., 2018). Further, accelerometers did not differentiate between sitting and standing postures, while the definition of sedentary behavior is posture specific. Although there is still not clear evidence on which accelerometer location better register PA levels, the present study shows that, at least from a cognitive-neuroelectric perspective, PA data from hip accelerometer location is more strongly related to neuroelectric activity than the wrist-based PA data. Further studies must confirm or contrast the present results.

With respect to sedentary time, no significant associations were observed with any of the behavioral or neuroelectric outcomes. Other studies have reported that only select sedentary behaviors (e.g., watching TV, playing videogames), but not total sedentary time may be associated to cognition (Johnson et al., 2007; Landhuis et al., 2007). However, the cut-point approach that we followed to process accelerometer data is insensitive to children's posture (e.g., reclining or lying) and cannot differentiate among sedentary behaviors. Little information is available in children on the relation for sedentary variables with neuroelectric activity underlying cognitive processes. Thus, it seems important for further studies to determine how different sedentary behaviors (i.e., screen-time, reading) could influence inhibition and neuroelectric activity in children.

Several mechanisms such as neurogenesis, angiogenesis, neural plasticity and neurotransmitters have been presented in the literature in an attempt to explain the beneficial role that fitness and PA play on brain health (Colcombe et al., 2004; Voss, Vivar, Kramer, & van Praag, 2013). Moreover, there is still scarce evidence on the mechanisms that may specifically explain the association between different components of physical fitness, PA, and the P3 component. However, the neuroinhibition hypothesis has been proposed as a possible determinant of this association (Kao et al., 2019; Polich, 2012). Under the perspective of this hypothesis, the P3 is considered to reflect the neural mechanism that inhibits extraneous brain activity to facilitate memory updating (Polich, 2012). The P3 may be helpful for understanding the potential of PA for improving executive function and brain activation in individuals who exhibit changes in P3 amplitude and latency. Although speculative, the P3 may serve to reflect alterations in proactive cognitive strategies and given the increased metabolic demands required for these processes (Braver, Gray, & Burgess, 2007), higher fitness level may favor the generation of necessary neuroelectric resources to engage proactive control mechanisms and therefore exhibit larger P3 amplitude. Further research is needed to shed light on the mechanisms explaining the association between fitness, PA and P3.

In a context where childhood obesity is declared as a pandemic, and knowing that obesity can affect brain health, there exists a fundamental neurobiological principle that states that cellular and molecular events in the brain are amenable to modification by external factors such as PA (van Praag, Kempermann, & Gage, 2000). In this context, since childhood overweigh or obesity is a marker of chronic inactivity and sedentarism (Must & Tybor, 2005), children with overweight or obesity who are sedentary may be more likely to benefit from PA than lean children. Collectively, stimulating brain health of those who need it most (i.e., children with overweight or obesity) through fitness and PA could have an impact in future generations.

The main limitation of the present study is the cross-sectional design, which does not allow us to draw causal interpretations. Furthermore, there are some physical activities (e.g., bicycling, swimming) that cannot be well-measured via accelerometry, and further such measurement cannot distinguish between types of sedentary behaviors. Another important limitation is the lack of cut-off points specifically validated in a sample of children with overweight or obesity, which may add error to the measurement and decreases precision of the PA estimates. The differences in data reduction make it difficult to compare the PA estimates with large epidemiological studies using data from NHANES or International Children's Accelerometry Database. Also, future studies should test cut-point-free PA metrics, such as the intensity gradient, to avoid spurious or undetected findings due to the use of unsuitable cut-points to participants. Future studies should test these outcome in relation to executive function and neuroelectric activity. Our conclusions are limited to a sample of Caucasian children with overweight or obesity. The main strength of this study was that, to the best of our knowledge, it is the first to investigate the relation between different physical fitness components, objectively measured sedentary time, and PA intensities with inhibitory control and neuroelectric outcomes in a sample of children with overweight or obesity. Other strengths include the objective and standardized assessments of physical fitness and neurocognitive variables as well as the use of data from different accelerometer locations (i.e., hip and non-dominant wrist).

Our results provide initial evidence to suggest that not only cardiorespiratory fitness, but also speed-agility, are associated with inhibitory control and P3 amplitude in children with overweight or obesity. There were no significant associations between upper limbs and lower limbs measurements of muscular strength, PA, or sedentary time and inhibitory control. The associations observed for vigorous PA with P3 amplitude, and for moderate PA with P3 latency were accelerometer location-dependent, since they disappeared when considering the findings from the nondominant wrist-based measure. Since physical fitness components may be differentially associated with inhibitory control and the neuroelectric activity subserving this aspect of cognition, promoting PA programs that enhances speed-agility and cardiorespiratory fitness, may be important for better understanding whether such health improvements benefit inhibitory control in youth with overweight or obesity.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

FIGURE S1 EEG data processing steps. Electroencephalography (EEG) data were processed using MATLAB (R2015b), EEGLab (13.5.4b), and ERPLAB (6.0) toolbox plug-ins. ASR has been previously supported by Chang, C.-Y., Hsu, S.-H., Pion-Tonachini, L., and Jung, T.-P. (2018). Evaluation of Artifact Subspace Reconstruction for Automatic EEG Artifact Removal. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (Vol. 2018, pp. 1242–1245). IEEE. ASR, artifact subspace reconstruction; ICA, independent component analysis; MARA, multiple artifact rejection algorithm

TABLE S1 Bivariate correlations between potential confounders and inhibitory control task and neuroelectric measurements

TABLE S2 Hierarchical regressions for the association of physical activity (PA) and sedentary time (non-dominant wrist) with inhibitory control for congruent and incongruent trials ($n = 84$)

TABLE S3 Hierarchical regressions for the association of physical activity (PA) and sedentary time (wrist) with P3 amplitude and latency for congruent and incongruent trials ($n = 84$)

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