

Original article

# Neurophysiological correlates of interference control and response inhibition processes in children and adolescents engaging in open- and closed-skill sports

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Received 5 August 2020; revised 18 September 2020; accepted 23 November 2020

Available online 6 January 2021

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## Abstract

**Background:** Accumulating evidence suggests that sports participation promotes the development of inhibitory control, but the influences of the sports category and inhibition type still remain unclear. The categorization of sports based on the open-skill (externally paced) and closed-skill (self-paced) continuum allows for the integration of the environment as a factor contributing to sports-related benefits for inhibitory control.

**Methods:** Cross-sectional data from different studies were combined ( $n = 184$ ) to examine the association between open- and closed-skill sports and cognitive control processes related to interference control and response inhibition. Participants (aged 9–14 years) filled in 7-day physical activity recall protocols and completed a Stroop Color–Word or a Go/NoGo task. The N200, N450, and P300 components of event-related potentials elicited by these tasks were recorded using electroencephalography.

**Results:** Partial correlations supported the belief that time spent in open-skill sports was related to higher performance on inhibition trials. Additionally, path analyses revealed an association between this sports type and a greater negativity in the N200 and N450 amplitudes in both the full sample and group-level analyses. In contrast, no relation was found between sports type and P300 amplitude.

**Conclusion:** The findings suggest that only the engagement in open-skill sports is associated with more effective conflict monitoring and higher performance on tasks demanding inhibitory control.

**Keywords:** Conflict monitoring; Event-related potentials; Exercise; Go/NoGo; Stroop Color–Word; Physical activity

## 1. Introduction

Inhibitory control is a key component common to all executive functions<sup>1</sup> and is characterized by fundamental conceptual gains in early preschool years, gradual refinements in childhood and a relatively late maturation in adolescence.<sup>2</sup> With regard to its subtypes, interference control (i.e., selective attention and cognitive inhibition) and response inhibition (i.e., suppressing impulsive behavior and resisting temptations) need to be differentiated.<sup>3</sup> The promotion of the development of these subtypes in childhood seems to be important because both have been found to be related to academic achievement<sup>4,5</sup> and mental health<sup>6</sup> in adolescence. In addition, poor response inhibition predicts unwanted and risky behaviors, such as

increased vulnerability to drug abuse and the risk of substance use disorder.<sup>7,8</sup> However, evidence suggests that inhibitory control and other executive functions are highly sensitive to direct and indirect training during childhood and adolescence.<sup>9</sup>

In this respect, meta-analytical findings suggest that there are small benefits from sports and physical activity programs on inhibitory control in these age groups.<sup>10</sup> The results of a comprehensive meta-regression further showed that the sports type moderates cognitive benefits independent of age, so that coordinative sports promise greater improvements across different cognitive domains than endurance, resistance, or mixed exercise types.<sup>11</sup> A high efficiency of coordinative exercise may be explained by its effect on fundamental movement skills, which are closely related to inhibitory control and other aspects of executive function,<sup>12,13</sup> probably due to a shared set of abilities and/or a common neural substrate.<sup>14,15</sup> Given the general decrease of physical activity following school entry,<sup>16</sup>

Peer review under responsibility of Shanghai University of Sport.

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the encouragement of participation in sports that promise benefits for inhibitory control is at least as relevant as the promotion of increases in overall dose. From a developmental perspective, knowledge of the efficiency of different sports types may be essential for the development of interventions targeting the promotion of this cognitive ability. However, previous studies have compared the cognitive benefits of different sports types mainly based on the employed energy system (i.e., aerobic vs. anaerobic exercise) and/or the body coordination required to perform sports-specific techniques. In contrast to these comparisons, the differentiation between open- and closed-skill sports allows for the integration of the environment as a potential factor contributing to cognitive enhancements. Whereas open-skill sports require athletes to react in a dynamically changing, unpredictable and externally paced environment, closed-skill sports are characterized by a predictable and static environment.<sup>17</sup> Such a differentiation of the sports category based on the variability, complexity, and predictability of the environment has previously been used to gain insights into athletes' neurocognitive profiles.<sup>18–22</sup> A review of the few existing observational studies (and even fewer interventional studies) provides a first indication that open-skill sports may elicit greater benefits for overall cognition than closed-skill sports.<sup>23</sup> It should be noted that this review is mainly based on studies in adult populations and did not differentiate between different types of inhibitory control.

Given the differences between open- and closed-skill sports, their relation to inhibitory control might be influenced by its examined subtype. Open-skill sports may place greater demands on response inhibition due to the need to stop or adjust one's own movements quickly in response to changes in the environment, such as unpredictable actions of team members or opponents.<sup>24</sup> In contrast, closed-skill sports do not require the inhibition of motor responses to a similar extent. Instead, participation in these sports likely requires a reliance on interference control to suppress unwanted feelings arising from fatigue and to select an appropriate pace independent from distractors in the surroundings.<sup>25</sup> The current evidence, albeit limited, suggests that open-skill athletes, but not closed-skill athletes, show better response inhibition than their inactive peers.<sup>19,20</sup> With regard to interference control, the results are less consistent: athletes who engage in open-skill or closed-skill sports either had superior behavioral performance in comparison to irregular exercisers<sup>26,27</sup> or demonstrated no differences.<sup>18,28</sup> Given the paucity of studies among children and adolescents, the role of the inhibition type on the association between sports type and inhibitory control in these populations remains unclear.

Moreover, the relation between these constructs has mainly been investigated using behavioral outcomes.<sup>23</sup> As a consequence, no conclusions can be drawn on the neurocognitive processes that account for variations in task performance. This limitation can be overcome by the utilization of event-related potentials (ERPs) related to inhibitory processing. Conflict monitoring and the allocation of attentional resources are key processes contributing to both interference control and response inhibition.<sup>29</sup> Conflict monitoring is indexed by the

N200 and N450 components elicited from the Go/NoGo (GNG)<sup>30</sup> and Stroop Color–Word (SCW) tasks, respectively.<sup>31</sup> Both components are negative-going amplitudes with a frontal/fronto–central distribution and a common neural generator in the anterior cingulate cortex.<sup>32,33</sup> The SCW and GNG tasks also elicit a positive-going amplitude that peaks at parietal/centro–parietal regions in children and adolescents.<sup>29,34,35</sup> This specific component has been termed P300, and its magnitude is suggested to be proportional to the allocation of attentional resources for the evaluation of task-relevant stimuli.<sup>36</sup> Both the ERP components of the conflict-monitoring family and P300 undergo developmental changes and therefore allow conclusions on the maturation of inhibition processes.<sup>34,37</sup> The current evidence suggests that athletes and non-athletes have different neurocognitive profiles, as indicated by differences in the N200–P300 complex elicited from a variety of visual and auditory cognitive tasks.<sup>38–40</sup> However, these neurocognitive markers have rarely been utilized to examine the association between different sports types and inhibitory control in children and adolescents.

In older adults, a greater P300 amplitude in the central regions compared to the frontal regions has been reported in participants with prolonged engagement in open-skill sports, whereas no differences between regions were found in irregular exercisers and peers with regular engagement in closed-skill sports.<sup>26</sup> The more focal activation pattern has been interpreted as higher neural efficiency. A similar study in the same age group further found that participants who engaged in open-skill sports had higher P300 and lower N200 amplitudes in comparison to peers performing closed-skill sports or no sports at all.<sup>27</sup> Although it is unclear if a similar pattern of results can be expected in children and adolescents due to their differences in the neurodevelopmental state,<sup>41,42</sup> these ERP components appear to be more sensitive to open-skill sports in particular. Moreover, it should be noted that findings on N200 and P300 in relation to sports type were limited to task paradigms demanding interference control.

The present study aimed to examine the association between regular engagement in open- and closed-skill sports and inhibitory control in healthy children and adolescents. Possible relations were investigated using both behavioral and neurophysiological indices of inhibitory control and were compared between tasks demanding interference control (SCW task) and response inhibition (GNG task). In contrast to previous studies, our study had a novel approach in that the time spent in each sports type was used to examine the relative contributions of open- and closed-skill sports to inhibitory control. Based on a recent review,<sup>23</sup> a positive association between regular engagement in sports and inhibitory control was expected for open-skill sports only. Given the indications provided by cross-sectional studies with older populations,<sup>26,27</sup> it was hypothesized that more effective conflict monitoring and the allocation of attentional resources would also be related to higher engagement in open-skill sports only.

## 2. Methods

### 2.1. Participants

For the current investigation, cross-sectional (and unpublished) data were combined from 4 studies that employed a similar assessment protocol to collect physical activity levels, inhibitory control and ERPs (Supplementary Fig. 1). Our combined analysis addressed an objective different from the individual studies' objectives. In total, 184 male and female children and adolescents were recruited from local schools in the greater area of Leipzig, Germany, and Basel, Switzerland. The combined sample included participants aged from 9 years to 14 years with right-hand dominance and corrected-to or normal vision. The presence of a mental disorder and/or any medical condition posing an increased health risk during physical activities were exclusion criteria that were common to the studies from which data were obtained. Following the explanation of possible risks and benefits associated with the study protocol, written informed consent was obtained from legal guardians of the participants. Additionally, study procedures were approved by the responsible ethics committees (Ethikkommission Nordwest- und Zentralschweiz) and were in line with the guidelines set forth in the Declaration of Helsinki.

### 2.2. Procedures

Using computer-based cognitive tasks, either the participants' interference control (Studies 1 and 2) or response inhibition (Studies 3 and 4) was assessed. Based on the employed inhibition task, participants were assigned to the SCW group or the GNG group. The ERPs elicited by both task types were recorded using electroencephalography. Cognitive testing was performed with 1 participant at a time in a dimly lit room with surrounding noise kept to a minimum. The inhibitory control task was not preceded by other cognitively and/or physically demanding assessments. Following the collection of anthropometric and demographic data, participants completed the Strengths and Difficulties Questionnaire and used a physical activity recall protocol to report the duration and intensity of all physical activities of at least moderate intensity within the last 7 days. The recall tool used has been found to be of adequate validity and reliability in children and adolescents.<sup>43</sup> In contrast to objective assessments of physical activity with accelerometry, the recall protocol used in the 4 studies further allowed a differentiation of types of activities. All assessments were performed during a single laboratory visit of 90- to 120-min duration.

### 2.3. Categorization of sports activities

The 7-day physical activity recall protocols were considered valid and were included in our statistical analysis if the recall period covered a regular school week. Recall protocols covering holidays were not included since children and adolescents' patterns of physical activity are likely to be less representative during holiday periods, given that many sports clubs do not offer physical activities during holidays. Trained raters blinded to the purpose of the current investigation recorded the physical activities included in valid recall protocols and categorized them

into open-skill sports, closed-skill sports, and unspecific physical activities. Discrepancies were resolved by a third expert. The unspecific category included all types of physical activities that could not be categorized as either open-skill or closed-skill sports. Examples of categorized sports and physical activities are provided in the Supplementary Table 1. The total time spent in the 3 categories (in min/week) was extracted for statistical analyses.

### 2.4. Cognitive tasks

Computer-based versions of the SCW and GNG tasks were administered with E-Prime 2.0 and E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA, USA), respectively. For both tasks, high test–retest reliability has been reported in children and adult populations.<sup>44,45</sup> During the SCW task, participants were instructed to respond to the color of a word, but not its meaning, by pressing 1 of 3 buttons on a serial response box. Visual stimuli were color words (Supplementary Fig. 2), which appeared in the same color on compatible trials (e.g., “green” presented in green color) and a different color on incompatible trials (e.g., “green” presented in blue color). The German color words “blau” (blue), “gelb” (yellow), and “grün” (green) were used in this task to ensure a similar visual content. Visual stimuli were presented against a black background for 200 ms, and responses were collected within 1500 ms after their onset. The inter-stimulus interval varied randomly between 1500 ms and 2000 ms to reduce the likelihood of guessing. Compatible and incompatible trials were presented with equal probability and in a fully randomized order. Following a practice round with 20 trials, all participants completed 4 blocks with 36 trials each (with a 30-s break between blocks). Average reaction times on response-correct compatible and incompatible trials were extracted for statistical analyses. Additionally, accuracy on both trial types was calculated for descriptive purposes.

During the GNG task, participants were instructed to press a button on a serial response box to 2 types of Go trials and suppress their motor response to NoGo trials. Visual stimuli were different geometric shapes with their contour-lines drawn either in pink, blue, or yellow (Supplementary Fig. 3). These colors were matched by intensity and brightness. Throughout the cognitive task, the 3 colors were assigned to GoFrequent, Go, and NoGo trials. Whereas Go and NoGo trials appeared with an equal probability of 0.3, GoFrequent were presented with a probability of 0.4. This approach was chosen so that the Go and NoGo trials could be compared without a possible confounding effect of frequency. Following an inter-stimulus interval that varied randomly between 1200 ms and 1400 ms, visual stimuli were shown for 150 ms, and responses were collected within 850 ms after their onset. Following a practice round with 20 trials, 3 blocks with 100 trials each (with a 30-s break between blocks) were administered. Commission error rates (i.e., pressing a button in response to NoGo trials) and omission error rates (i.e., pressing no button in response to Go trials) were calculated and extracted for statistical analyses.

Additionally, reaction time on response-correct GoFrequent trials was calculated for descriptive purposes.

### 2.5. ERPs

ERPs elicited by the SCW task were recorded using 64 passive electrodes integrated in the HydroCel Geodesic Sensor Net (Electrical Geodesics Inc., Eugene, OR, USA). Most electrode positions corresponded to the international 10:10 system; and additional electrodes above, below, and next to the eyes recorded the vertical electrooculogram and horizontal electrooculogram. Prior to data collection, scalp electrode impedances were controlled and reduced below 50 K $\Omega$ . Data were referenced to the vertex channel, band-pass filtered (0.01–100 Hz), amplified and digitized at a sampling rate of 250 Hz using the Net Amps 300 (Electrical Geodesics Inc.).

Electroencephalographic activity during the GNG task was recorded from a flexible head cap with 64 active electrodes (ActiCap; Brain Products GmbH, Gilching, Germany), which was mounted to the participant's head. Electrode positions corresponded to the 10:10 system. AFz served as ground and Cz as online reference. The recordings were initialized when at least 90% of all electrodes showed scalp impedances below 10 K $\Omega$ , which was supported by the application of a highly conductive gel. The ActiCHamp (Brain Products GmbH) was used to amplify the data and digitize them with a pass-band of 0.01–100 Hz and at a sampling rate of 500 Hz.

BESA Research 7.0 (Brain Electrical Source Analysis GmbH, Gräfelfing, Germany) was used for offline processing of collected data. Based on (virtual) horizontal electrooculogram and vertical electrooculogram channels, blinks were detected and removed by employing automatic adaptive artefact correction. This approach uses principal component analysis to separate artefact components from brain signals. Subsequently, electroencephalogram (EEG) data were high-pass filtered (forward phase shift of 0.1 Hz; slope 6 dB/octave) and baseline corrected using the time period from –200 ms to stimulus onset. Blinks that survived the correction approach and other artefacts were rejected based on individual amplitude (SCW:  $143 \pm 23.3 \mu\text{V}$ ; GNG:  $118 \pm 19.9 \mu\text{V}$ ; mean  $\pm$  SD) and gradient (SCW:  $75 \pm 5 \mu\text{V}$ ; GNG:  $75 \pm 3 \mu\text{V}$ ) thresholds. Artefact-free segments (with correct behavioral responses) covering a latency range from –200 ms to 800 ms relative to stimulus onset were averaged for the different trial types in the SCW and GNG tasks. The resulting segments were low-pass filtered (zero-phase shift of 30 Hz; slope 24 dB/octave), and the reference was changed to average mastoids.

The selection of the latency range and regions to derive the ERP components was based on previous research and inspection of the data.<sup>35,46,47</sup> The P300 was calculated as the mean amplitude in the 270 ms to 370 ms latency range at the parieto-occipital region (average of Pz, PO3, and PO4, electrode between P1 and P3, electrode between P2 and P4) for the SCW task and as the mean amplitude in the 400–600 ms latency range at the centro-parietal region (average of Pz, P1, P2, CPz, CP1, and CP2) for the GNG task. The P300 elicited

by the GNG task was extracted from this region because this component shows a different topography in children compared to adults (i.e., fronto-central distribution), probably due to the immaturity of the prefrontal cortex.<sup>34,37</sup> The N450 elicited by the SCW and the N200 elicited by the GNG task were assessed from the mean amplitude in the 400 ms to 500 ms latency range at the frontal region (average of Fz, F1, F2, F3, and F4) and the mean amplitude in the 250 ms to 350 ms latency range at the fronto-central region (average of Fz, F1, F2, FCz, FC1, and FC2), respectively. Differences between groups regarding the electrodes that were combined for the regions of interest were due to slightly different peaks and different layouts of the employed EEG caps or sensor nets. The P300, N200, and N450 components were extracted separately for the different trial types in each cognitive task and further used for statistical analyses.

### 2.6. Statistical analyses

The statistical analyses of collected data were performed with SPSS Version 25.0 (IBM Corp., Armonk, NY, USA) and the AMOS Version 25.0 graphical interface (IBM Corp.). The Shapiro–Wilk test was employed to check whether data followed a Gaussian distribution. For variables showing a non-normal distribution,  $z$ -values of 3.29 or higher for skewness and/or kurtosis, log-transformation was applied. To be able to assess correlations between outcomes across the full sample despite differences in the EEG system and different behavioral performance parameters, ERP components and performance measures were  $z$ -standardized within the SCW and GNG groups. Although N200 and N450 are different components, they were combined in the full sample analysis, because a review supports both components to index a similar cognitive control process.<sup>32</sup> For single-group analyses, absolute values were used; and for full-sample analyses, the  $z$ -standardized values were included as main outcomes. Behavioral performance indices used as dependent variables were compatible/incompatible reaction times in the SCW group and omission/commission error rates in the GNG group, so that cognitive performance on trials with low and high inhibitory demands was operationalized from the same outcome type within each group. Prior to hypotheses testing, zero-order correlations between potential confounders and outcomes were calculated separately for the SCW and GNG groups, as well as for the full sample. Variables showing at least a weak correlation ( $r \geq 0.1$  or  $r \leq -0.1$ ) or a statistically significant correlation with one or more outcomes were accounted for in subsequent main analyses. The association between sports type and behavioral performance was examined from partial correlations, which controlled for the other 2 sports types and potential confounders, if necessary. The level of statistical significance was set to  $p < 0.05$ . Subsequently, path-analyses were employed to investigate the relation between the engagement in different sports types and ERP components. Models were specified that included total time spent in open-skill, closed-skill, and unspecific physical activities as predictors and N200, N450, as well as P300 as dependent variables. Interdependencies were



accounted for by estimating covariance between sports types and covariance between ERP components. Separate models were specified and tested for trials with low (compatible trials, Go trials) and high demands (incompatible trials, NoGo trials) on inhibitory control. In case of missing data on background variables, the full information maximum likelihood approach was employed, since this method proved to be more effective and less biased than other algorithms in a simulation study.<sup>48</sup> The relative strengths of possible associations between variables were assessed from standardized  $\beta$ , and  $t$  tests were employed to test whether coefficients equaled zero. For the examination of individual paths, this hypothesis was rejected at  $p < 0.05$ . The fit of the models to the data was assessed by calculating absolute and relative fit indices. For the given sample size, model fit was considered good if the following criteria were met: root mean square error of approximation (RMSEA)  $\leq 0.08$ <sup>49</sup> and  $\chi^2/df \leq 2$ .<sup>50</sup>

### 3. Results

EEG data from 5 participants were not included in the statistical analyses due to severe contamination by movement artefacts. The anthropometrics, psychopathology, ERP components, and the number of segments used for averaging for the remaining participants are shown in Table 1. Zero-order correlations between sex, age, body mass index, and Strengths and Difficulties Questionnaire score and predictors as well as outcomes exceeded the prespecified threshold of  $r \geq 0.1$  or  $r \leq -0.1$  and were therefore considered as covariates in subsequent regressions and path-analyses (Supplementary Tables 2–4). Because the pattern of zero-order correlations differed between both groups and the full sample, the selection of covariates was adjusted based on the analyzed groups.

Table 1  
Anthropometrics, psychopathology, ERPs elicited by the inhibitory control tasks, and total number of averaged segments (mean  $\pm$  SD) for the SCW group, GNG group, and the full sample.

	SCW ( <i>n</i> = 39F/50M)	GNG ( <i>n</i> = 36F/54M)	Total ( <i>n</i> = 75F/104M)
<b>Anthropometrics</b>			
Age (year)	11.2 $\pm$ 1.2	10.7 $\pm$ 1.4	10.9 $\pm$ 1.3
Body mass (kg)	43.2 $\pm$ 10.6	40.3 $\pm$ 10.9	41.7 $\pm$ 10.8
Body mass index (kg/m <sup>2</sup> )	18.5 $\pm$ 3.3	17.9 $\pm$ 2.9	18.2 $\pm$ 3.1
<b>Psychopathology (SDQ total score)</b>	13.5 $\pm$ 3.9	10.4 $\pm$ 4.2	11.9 $\pm$ 4.4
<b>Sports type (min/week)</b>			
Open-skill sports	136.6 $\pm$ 146.6	206.0 $\pm$ 136.9	171.5 $\pm$ 145.6
Closed-skill sports	211.2 $\pm$ 246.2	104.6 $\pm$ 174.0	157.6 $\pm$ 219.0
Total PA	452.9 $\pm$ 312.2	316.0 $\pm$ 188.3	384.1 $\pm$ 265.8
<b>Compatible and Go trials</b>			
N200/N450 ( $\mu$ V)	-0.01 $\pm$ 4.16	-2.04 $\pm$ 4.02	—
P300 ( $\mu$ V)	9.55 $\pm$ 4.92	11.98 $\pm$ 5.39	—
Number of good segments	47.3 $\pm$ 7.8	67.2 $\pm$ 10.9	—
<b>Incompatible and NoGo trials</b>			
N200/N450 ( $\mu$ V)	-0.54 $\pm$ 4.07	-1.99 $\pm$ 4.38	—
P300 ( $\mu$ V)	9.41 $\pm$ 5.07	12.00 $\pm$ 5.13	—
Number of good segments	46.3 $\pm$ 6.7	49.4 $\pm$ 12.0	—

Notes: Compatible and incompatible trials were administered in the SCW group. Go and NoGo trials were administered in the GNG group. The N450 and N200 were elicited by the inhibitory control tasks in the SCW and GNG groups, respectively.

Abbreviations: ERPs = event-related potentials; F = female; GNG = Go/NoGo task group; M = male; PA = physical activity; SCW = Stroop Color–Word task group; SDQ = Strengths and Difficulties Questionnaire.

### 3.1. Behavioral performance

The participants' behavioral performance on the SCW and GNG tasks are shown in Fig. 1. Based on the analysis of the full sample, partial correlations correcting for other sports types and potential confounders revealed that more time spent in open-skill sports was associated with greater performance on trials demanding a high inhibitory control ( $r = -0.21$ ,  $p = 0.005$ ). A similar trend was observed between the time spent in closed-skill sports and this behavioral outcome, but this relation did not reach a statistically significant level ( $r = -0.13$ ,  $p = 0.082$ ). When partial correlations were examined within groups, the pattern of the results differed between the SCW and GNG groups. Whereas more time spent in open-skill sports was related to lower reaction time on both compatible ( $r = -0.36$ ,  $p = 0.001$ ) and incompatible trials ( $r = -0.35$ ,  $p = 0.001$ ) in the SCW group, no association was found between prolonged engagement in this type of sports and commission as well as omission error rate. In contrast, more time spent in unspecific sports was correlated with a higher commission error rate ( $r = 0.28$ ,  $p = 0.010$ ). In both groups, there was no association between prolonged engagement in closed-skill sports and behavioral performance (Table 2).

### 3.2. ERPs

The ERP waveforms and topographical distributions of the N200, N450, and P300 components for the analyzed trial types are shown in Fig. 2. Path-analyses applied to the full sample revealed that only the time spent in open-skill sports predicted the amplitudes of the N450/N200 components elicited from trials with high inhibitory demand (incompatible trials, NoGo trials) ( $\beta = -0.24$ ,  $p = 0.002$ ) (Fig. 3A). A similar pattern of

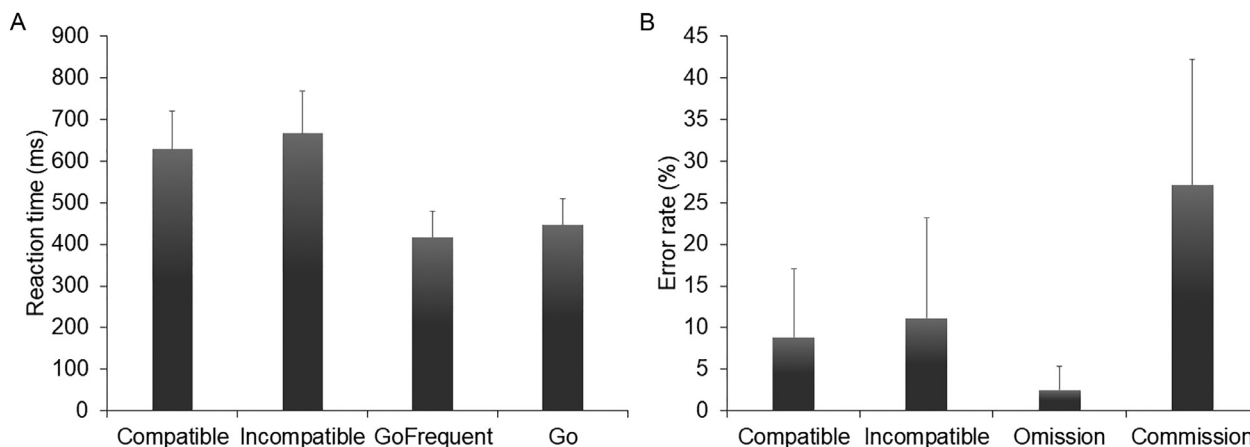


Fig. 1. Reaction time (A) and error rates (B) on the different trial types in the Stroop Color–Word and Go/NoGo tasks.

results was obtained on the group-level, since participants in SCW and GNG groups with prolonged engagement in open-skill sports also showed a greater negativity of the N450 amplitudes ( $\beta = -0.23$ ,  $p = 0.028$ ) (Fig. 3B) and N200 amplitudes ( $\beta = -0.23$ ,  $p = 0.037$ ) (Fig. 3C), respectively. However, this association was only observed for incompatible and NoGo trials. For the P300, both the group-level and full-sample analyses did not support a relation between its amplitude and the time spent in different sports types. Moreover, this result was consistent across the examined trial types (Supplementary Fig. 4). There was a good fit of the models investigating the association between time spent in different sports types and ERPs elicited by both trials with low inhibitory demand ( $RMSEA \leq 0.05$ ,  $\chi^2/df \leq 1.42$ ) and high inhibitory demand ( $RMSEA \leq 0.05$ ,  $\chi^2/df \leq 1.47$ ).

#### 4. Discussion

With regard to behavioral performance, the analysis of the full sample indicated a positive association between time spent in open-skill sports and task performance on trials with high demands on inhibitory control. The engagement in closed-skill sports and unspecific physical activities, however, did not account for variance in the inhibitory aspect of executive function. A similar pattern of results was obtained for ERP

components that indexed conflict monitoring, because only time spent in open-skill sports was related to greater negativity of the N200 and N450 amplitudes in response to trials with high inhibitory demands. In contrast, there was no association between the sports types and P300 amplitude for any of the analyzed trial types.

When the full sample was considered, path-analysis revealed greater inhibitory control in participants with prolonged engagement in open-skill sports. This finding is in line with a review suggesting that open-skill sports promise higher cognitive benefits than other sports types.<sup>23</sup> At the same time, our findings are in conflict with the observation that both open- and closed-skill athletes outperform irregular exercisers on tasks tapping inhibitory control.<sup>26,27</sup> The lack of an association between time spent in closed-skill sports and this component of executive function might partly be explained by methodological differences. Whereas previous studies formed groups that engaged in 1 sports type only, our study used continuous data and accounted for the engagement in different sports and physical activities by calculating partial correlations. This approach was chosen because children and adolescents, in comparison to older populations, are unlikely to engage in 1 sports type only.<sup>51</sup> Thus, the results reflect the relative contributions of open- and closed-skill sports, as well as unspecific activities, to inhibitory control. The comparison of

Table 2

Partial correlations between open-skill sports, closed-skill sports, and unspecific sports and behavioral performance on the inhibitory control tasks, controlling for other sports types, and potential confounders in the SCW group, GNG group, and the full sample.

	SCW (reaction time)		GNG (error rate)			Total (z-score)	
	Com.	Incom.	Go trials <sup>a</sup>	Omission	Commission	Com./Go trials	Incom./NoGo trials
Open-skill sports	-0.36*	-0.35*	-0.06	0.18	-0.13	-0.11	-0.21*
Closed-skill sports	-0.18	-0.18	-0.16	0.02	0.09	-0.13	-0.13
Unspecific PA	-0.04	-0.02	-0.23*	0.19	0.28*	-0.04	-0.04

Notes: Partial correlations between a specific sports type and behavioral performance were controlled for the other 2 sports types. Additional covariates were sex, age, body mass index, and SDQ total score in both the SCW and GNG groups and age and SDQ total score in the full sample.

<sup>a</sup> Reaction time on Go trials.

\*  $p < 0.05$ , correlation coefficient differs statistically significant from zero.

Abbreviations: Com. = compatible trials; GNG = Go/NoGo task group; Incom. = incompatible trials; PA = physical activity; SCW = Stroop Color–Word task group; SDQ = Strengths and Difficulties Questionnaire.

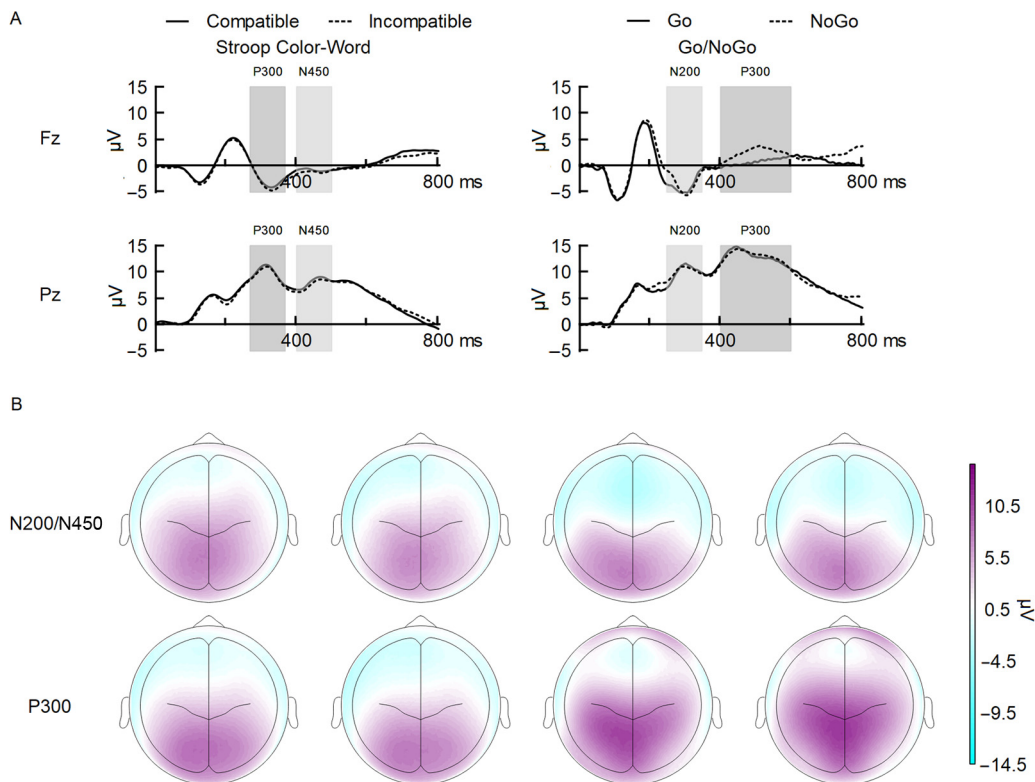


Fig. 2. (A) Event-related potential waveforms at Fz and Pz and (B) topographical distributions of the N200, N450, and P300 components elicited by the trials with low and high inhibitory demand in the Stroop Color–Word and Go/NoGo tasks. The N450 was assessed from the Stroop Color–Word task, and the N200 was assessed from the Go/NoGo task. The topographic plots are averaged over the latency range used to calculate the N200 (250–350 ms), N450 (400–500 ms), and P300 (Stroop Color–Word: 270–370 ms; Go/NoGo: 400–600 ms) components.

partial correlations between groups revealed a similar direction of the association between time spent in open-skill sports and behavioral performance but revealed a stronger correlation in the SCW relative to the GNG group. Consequently, this indicates that the pattern of results in the full-sample analysis is mostly driven by the link between engagement in open-skill sports and interference control.

Previous studies have reported that both aerobic exercise and motor skills explain unique proportions of variance in interference control.<sup>13,52</sup> Acute open- and closed-skill training has been associated with high physical demands, but acute open-skill training has been characterized by additional cognitive/coordination demands due to greater movement complexity.<sup>53</sup> Thus, a lack of an association between closed-skill sports engagement and inhibitory control, when controlling for time spent in open-skill sports, could be explained by a common physiological strain. In contrast, the coordinative component seems to be the key to eliciting cognitive improvements, since meta-analytical findings support a greater efficiency of coordinative exercise types in comparison to aerobic, resistance, or mixed exercise.<sup>11</sup> With a few exceptions, most sports with high coordinative demands fall into the open-skill category; thus, our behavioral findings might be attributed to the link between complex motor skills and interference control.

In addition to better performance on trials with high demand on inhibitory control, our full-sample analysis further

showed a greater negativity of ERP components related to the conflict-monitoring family in participants with prolonged engagement in open-skill sports. This pattern of results was independent of the inhibition type, given that more time spent in open-skill sports was related to greater negativity of the N200 and N450 in the GNG and SCW groups, respectively. Both components share the anterior cingulate cortex as the neural generator<sup>54,55</sup> and reflect conflict-monitoring processes. However, the N200 elicited from NoGo trials is related to response conflict,<sup>47</sup> whereas the N450 elicited from incompatible trials of the SCW task provides a measure of the detection of stimulus conflict.<sup>46</sup> Consequently, our findings support an association between the engagement in open-skill sports and both types of conflict monitoring. Previous studies have already shown that greater negativity of the N450 amplitude was detected along with improved interference control following acute<sup>56</sup> and long-term physical activity<sup>57</sup> in older populations. Additionally, N450 amplitude has been found to mediate the cognitive benefits of increased physical fitness.<sup>58</sup> A greater negativity of the N200 amplitude also seems to be favorable because this pattern has been related to successful inhibitions on NoGo trials in children and adolescents.<sup>35</sup> Consequently, the inverse relation between time spent in open-skill sports and the N200 amplitude, as well as the N450 amplitude, indicates more effective conflict monitoring that may contribute to greater inhibitory control. The need to detect stimulus or response conflict to allow adjustments in subsequent cognitive

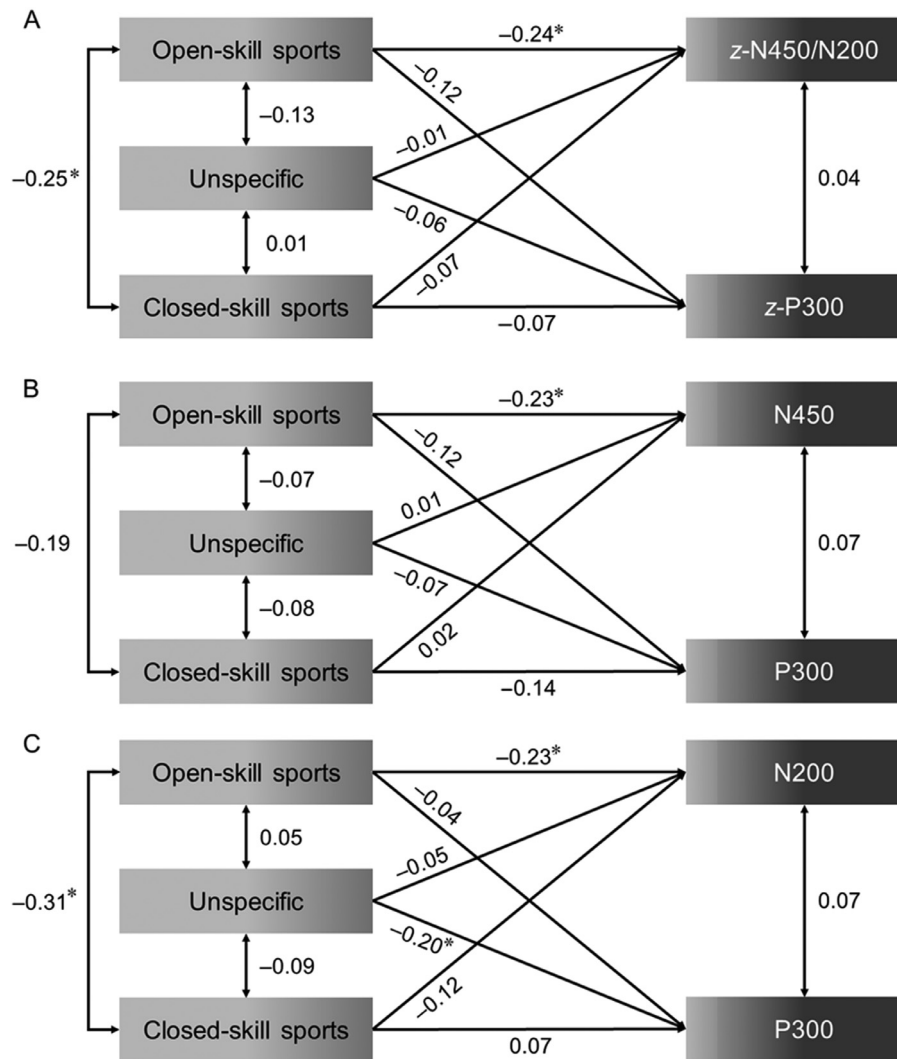


Fig. 3. Path analyses investigating the association between different sports types and N450/N200 as well as P300 amplitudes elicited by trials with high inhibitory demand (incompatible/NoGo trials) in (A) the full sample, (B) the Stroop Color–Word group, and (C) the Go/NoGo group. Models were corrected for age, sex, psychopathology, and body mass index. Models investigating associations between sports types and event-related potential components elicited by trials with low inhibitory demand can be found in the Supplementary Figures and Tables. \*  $p < 0.05$ , standardized regression coefficient differs statistically significant from zero.

processing might account for such a relation.<sup>32</sup> This is further supported since the N200 and N450 components have been suggested to index anterior cingulate cortex-mediated signaling for flexible and compensatory adjustments in cognitive control.<sup>33</sup>

In contrast to conflict monitoring, the allocation of attentional resources towards task-relevant stimuli indexed by P300 was not related to any of the examined sports types. Similarly, a lack of differences in P300, which was elicited from inhibitory control or attention tasks, between open- and closed-skill athletes and non-athletes has been reported in adults previously.<sup>21,22</sup> Therefore, this cognitive process does not seem to account for greater behavioral performance in participants with prolonged engagement in open-skill sports, although the P300 has been suggested to contribute to both interference control and response inhibition.<sup>29</sup> To some extent, our results contradict the accumulating evidence in support of a modulation of P300 amplitude by aerobic exercise and cardiorespiratory fitness across age-groups.<sup>59</sup> Because most sports that mainly

target cardiorespiratory fitness can be categorized as closed-skill sports, a relation between this type and P300 could have been expected. However, it is likely that such association is more pronounced for skill-based outcomes rather than the engagement in sports that promote this skill. In this respect, cardiorespiratory fitness and P300 amplitude are both subject to genetic factors,<sup>34,60</sup> which limits the likelihood of detecting associations between P300 and the actual sports engagement.

The novel insights on the association between children and adolescents' conflict-monitoring abilities and time spent in open-skill sports should be interpreted with caution due to the cross-sectional nature of our study. Although a few intervention studies covered in one review have already shown that open- and closed-skill sports elicit cognitive benefits,<sup>23</sup> the direction of the effects in our study remain unclear. Consequently, the associations found between open-skill sports and conflict monitoring could also be due to children and adolescents with superior inhibitory control having a preference for this sports type. Another limitation of our study is the assessment of sports participation



using the 7-day physical activity recall. This instrument relies on the recall abilities of the participant and may introduce bias due to subjective reporting. However, there is currently no cost-effective alternative, since objective assessments of physical activity with accelerometry do not allow for the examination of the sports type. With regard to the magnitude of the correlations between the sports types and neurophysiological indices of inhibitory control, it cannot be excluded that considering additional confounders, such as pubertal status and intelligence, would have affected the results. In this respect, the developmental stage has previously been associated with sex- and domain-specific differences in brain plasticity, although it should be noted that there is limited evidence on the influence of the onset of puberty on response inhibition in particular.<sup>61</sup> Recalling that sex, age, psychopathology, and body mass index have been frequently reported to account for individual differences in the selected ERP components<sup>34,35</sup> and behavioral performance,<sup>11,62</sup> many important confounders have been accounted for in path analyses. Moreover, the results of the full-sample analyses might have been affected by different EEG recording systems in the SCW and GNG groups. Although the EEG was recorded from 64 electrodes in both groups, the electrode positions differed, so that the N200/N450 and P300 components could not be assessed from exactly the same regions. However, the topographic plots support the notion that the regions used to calculate the average amplitude for each component captured the local distribution of their peaks. Additionally, outcomes were *z*-transformed to overcome the limited comparability of absolute values in behavioral and neurophysiological indices of inhibitory control between the different groups and employed tasks.

## 5. Conclusion

In contrast to time spent with closed-skill sports, prolonged engagement in open-skill sports is associated with high inhibitory control. Given the links among this aspect of executive function, academic achievement and mental health, open-skill sports may aid children and adolescents in developing their potential in different domains of life. The neurophysiological evidence further indicates that individuals with regular engagement in open-skill sports show a neurocognitive profile characterized by more effective conflict monitoring. With regard to sports performance, this may be associated with greater ability to monitor conflicts even in real-life sports situations that require both the execution of complex movements and cognitive control (i.e., dual-tasks). Moreover, conflict monitoring appears to be one of the mechanisms underlying the association between the sports category and behavioral performance on inhibitory control tasks.

## Acknowledgments

The present study used data from the Martial Arts and Neurocognitive Indices of Executive Function (MANIEX) study, which was funded by the Opo Foundation (No. 2018-39) and the Freiwillige Akademische Gesellschaft Basel (No. 2018-11). Neither funder was involved in the conceptualization and conduct of the study.

## Authors' contributions

SL played a role in conceiving and designing the study, overseeing and performing data collection, project administration, formal analysis, funding acquisition, and drafting and editing this manuscript; MM played a role in overseeing and performing data collection and editing this manuscript; CA played a role in overseeing and performing data collection, project administration, and editing this manuscript; MG played a role in conceiving and designing the study, and editing this manuscript; UP played a role in conceiving and designing the study, project administration, and reviewing and editing this manuscript. All author have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

## Competing interests

The authors declare that they have no competing interests.

## Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jshs.2021.01.001.

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