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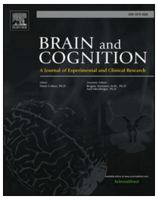

Up-regulation of proactive control is associated with beneficial effects of a childhood gymnastics program on response preparation and working memory

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ABSTRACT

The current study focused on the effects of an 8-week motor skill-based physical activity (i.e., gymnastics) program on the contingent negative variation derived from event-related brain potentials (CNV-ERP) during a working memory task in children. Children aged 7–10 years old were assigned to a gymnastics group (n = 26) or a wait-list control group (n = 24). The gymnastics group engaged in a gymnastics program whereas children in the control group were asked to maintain their typical routine during the intervention period. Working memory performance was measured by a delayed-matching working memory task, accompanied by CNV-ERP collection. The results revealed significant improvement of response accuracy from pre-test to post-test in the gymnastic group regardless of memory demands. Moreover, significant increase from pre-test to post-test in the initial CNV was observed in the gymnastic group regardless of memory demands. Bivariate correlations further indicated that, in the gymnastic group, increases in response accuracy from pre-test to post-test were correlated with increases in initial CNV from pre-test to post-test in task conditions with lower and higher memory loads. Overall, the current findings suggest that up-regulation of proactive control may characterize the beneficial effects of childhood motor skill-based physical activity on working memory.

1. Introduction

A growing body of literature has investigated the relationship between motor skill and cognitive development in children (van der Fels et al., 2015). Motor skill is the fundamental ability to perform goal-directed behavior and movements (e.g., object control, hand-eye coordination, bilateral coordination, dynamic, and static balance) (Jaakkola, Yli-Piipari, Huotari, Watt, & Liukkonen, 2016; Robinson et al., 2015) requiring the involvement of cognitive operations such as perception, sequencing, and monitoring (Roebers & Kauer, 2009). Best (2010) indicated that motor skill affects cognition through different pathways than other fitness dimensions (e.g., cardiovascular fitness); rather than stimulating brain function by means of indirect biological/physiological pathways, motor skill seems to act via the underlying mental operations it shares with higher-order cognitions. As such, the relationship between motor skill and cognition could be mediated by shared neural substrates underlying complex movement skills and cognitive tasks, including the prefrontal cortex, basal ganglia, and cerebellum (Leisman, Moustafa, & Shafir, 2016).

One aspect of cognition that has received recent attention is the relationship between motor skills and working memory (Hsieh, Lin, Chang, Huang, & Hung, 2017; Ludyga, Herrmann, et al., 2018). Working memory is a key component of cognitive control that represents a hierarchical system involving the short-term, transitory storage and

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manipulation of information in the service of motivated behavior (Baddeley, 1992). A substantial body of evidence suggests that working memory is a reliable predictor of various cognitive skills such as fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999), as well as academic achievement including reading, mathematics (Alloway, 2009), and language comprehension (Nation, Adams, Bowyer-Crane, & Snowling, 1999). On the other hand, working memory is thought to underlie successful motor adaptation and motor sequence learning (Seidler, Bo, & Anguera, 2012), which are both supported by activation of the frontal-parietal network (i.e., right dorsolateral prefrontal cortex, bilateral posterior parietal cortices) when performing complex motor and working memory tasks (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010). However, to date the majority of research on the association of motor skill and working memory during childhood are cross-sectional in nature (Ludyga, Herrmann, et al., 2018; van der Fels et al., 2015), which preclude causal inference. To gain stronger insights into the relationship between motor skill and working memory during childhood, longitudinal/interventional study is necessary.

Few studies have implemented a motor skill-based physical activity program (i.e., physical activity interventions that are designated to train various dimensions of motor skill) and gauged its effects on childhood working memory. For example, Koutsandreou, Wegner, Niemann, and Budde (2016) investigate the differential effects of a 10-week cardiovascular physical activity program versus a motor skill physical activity program on children's working memory, and found that while both interventions improved working memory (i.e., increased response accuracy) from pre- to post-test, the motor skill group was higher in response accuracy relative to control group at post-test. In addition, Hsieh et al. (2017) examined the effects of an 8-week gymnastics program, which is assumed to be motor skill-based, on working memory in children aged 7–10 years old. The results indicated significant improvement in response accuracy regardless of memory load following 8 weeks of gymnastics training. Moreover, the gymnastics group was higher in response accuracy relative to the control group at post-test.

In addition to behavioral measures of working memory, it would be informative to utilize electrophysiological assessments (including event-related brain potentials [ERP]) to study the neural processes subserving working memory. ERPs afford temporally sophisticated measurement of changes in neuroelectric activity that underpin distinct cognitive operations. In particular, our earlier study (Hsieh et al., 2017) observed greater attentional engagement, as signified by larger amplitude of the P3 component from ERP (P3-ERP) over posterior scalp site, during the retrieval phase of a working memory task following 8 weeks of motor skills program in school-aged children. This finding attests improved ability to invest attentional resources to imperative stimuli (Polich, 2007) during working memory retrieval in association with motor skills-based physical activity. Nevertheless, the study of Hsieh et al. (2017) only looked into cognitive processes during working memory retrieval, and therefore precludes understanding of neural substrates underlying other stages of working memory, such as those preceding the retrieval period (e.g., the response preparation period consisting of stimulus encoding and maintenance). Since neural substrates underlying the encoding (e.g., frontal-parietal network) (Majerus, Salmon, & Attout, 2013) and maintenance (e.g., lateral prefrontal cortex, frontal-temporal network) (Sato et al., 2018) of stimuli are related to complex motor activities (Mattfeld & Stark, 2010; Ptak, Schnider, & Fellrath, 2017), it would be interesting to investigate the causal effects of motor skill-based physical activity on neuroelectric function that underpin these subdomains of working memory.

Here, we utilized the contingent negative variation from ERP (CNV-ERP) to better understand neural modulations during working memory encoding and maintenance. The CNV-ERP is a negative-going potential that is evoked between the encoding stimulus and imperative stimulus during a two-stimulus (S1-S2) task. In general, the CNV is comprised of two subcomponents, the initial CNV (iCNV) and terminal CNV (tCNV), under task conditions in which the S1-S2 interval is long enough (e.g., at least 2 s; Kamijo et al., 2011; Ludyga, Gerber, Kamijo, Brand, & Pühse, 2018) for both components to emerge. The iCNV, which develops around one second after the onset of the warning signal (i.e., S1), reflects the processes of stimulus orientation and encoding (Rohrbaugh & Gaillard, 1983), with larger amplitude (i.e., more negative) reflecting better active maintenance of task information (Kamijo et al., 2011; Ludyga, Herrmann, et al., 2018; Ludyga et al., in press). In contrast, the tCNV, which is assessed before the onset of an imperative stimulus (i.e., S2) or a response, represents the processes of stimulus anticipation or response preparation (Rohrbaugh & Gaillard, 1983), with larger amplitude prior to S2 indicating a reactivation of goal-relevant information in a 'just-in-time' manner (Kamijo, O'Leary, Pontifex, Themanson, & Hillman, 2010). Previously, cross-sectional research (Ludyga, Herrmann, et al., 2018) on the association of motor skill with CNVs in adolescents have found a relationship between greater motor skill and larger iCNV amplitude, but not tCNV amplitude. Another longitudinal study in children (Ludyga et al., in press) revealed that increased motor skill predicted larger increases in iCNV amplitude, but not tCNV amplitude, from baseline to follow-up, suggesting that children with better motor skill could simultaneously have better stimulus encoding and maintenance of task goal during response preparation in a S1-S2 working memory task. Further, recent data also indicated a relationship between iCNV and proactive control when following a 'hard task' cue, suggesting that individuals proactively implement cognitive control during response preparation when a cognitive-demanding task is expected (De Loof et al., 2019). Considering that better proactive control during childhood may reflect greater maturation of the frontal-parietal networks that are responsible for better learning of motor skills (Ludyga, Herrmann, et al., 2018; Ludyga et al., in press) as well as better development of working memory (Segalowitz, Santesso, & Jetha, 2010), examinations into whether a motor skill-based physical activity program results in enhanced up-regulation of proactive control, as reflected by larger iCNV, during working memory task performance could expand the current literature on childhood motor and cognitive development.

Accordingly, the aim of the current study was to examine the effects of a motor skill-based physical activity on CNVs modulations during tasks that manipulate working memory demands in children. Based on previous studies (Hsieh et al., 2017; Koutsandreou et al., 2016), we hypothesized that a motor skill-based intervention would improve behavioral outcomes of working memory (i.e., higher response accuracy). We further hypothesized an increase in iCNV amplitude (i.e., more negative) following a motor skill training, whereas no such changes would be observed for the tCNV. Findings from the current study could provide insights into designing effective physical activity interventions to favor working memory development in children.

2. Methods

This investigation represents a secondary analysis of the previously published gymnastics physical activity program dataset (Hsieh et al., 2017). In the previous paper, the correct trial with reaction time (RT) and response accuracy were reported along with the P3-ERP outcomes. In this secondary analysis, our aim was to assess proactive/reactive control using the CNV-ERP elicited during the encoding and maintenance phase of a S1-S2 working memory task. Behavioral outcomes reported herein that overlap with Hsieh et al. (2017) are presented only to better inform the novel CNVs findings.

2.1. Participants

Fifty-two children between 7 and 10 years old were recruited from the greater Taipei area. This sample size was determined based on an a priori power analysis using G*Power 3.1. Based on the effect sizes of childhood physical activity intervention on working memory performance (i.e., response accuracy) ($\eta^2_p = .15$) and CNV-ERP ($\eta^2_p = .26$) reported in a previous study (Kamijo et al., 2011), a sample size of 48 participants is satisfactory to reach a power of 0.80 at an alpha level of 0.05. We over-recruited participants to account for dropouts or data integrity issues. The current study utilized a non-randomized controlled design. Specifically, children residing in Yilan county enrolled in an 8-week gymnastics group (n = 26) whereas children residing in Taipei city enrolled in a wait-list control group (n = 26). The gymnastics and wait-list control groups were recruited from different areas due to practical limitation (i.e., availability of gymnasium that could accommodate the number of participants and the designed gymnastics activities). None of the children received special education services related to cognitive, developmental, or attentional disorders. Children and their legal guardians were provided with informed written consent and assent in the format approved by the institutional review board of the National Taiwan Normal University (approval number: 201505HM004). All study procedures were carried out in accordance with the declaration of Helsinki. Inclusion criteria were as follows: (1) right-handed, as confirmed by the Edinburgh Handedness Inventory (EHI), (2) normal or corrected-to-normal vision confirmed by parental verbal report, (3) free from physical disabilities that could be exacerbated by performing physical activity, (4) absence of doctor-diagnosed neurological or attention disorders, (5) absence of any medical conditions listed on the Physical Activity Readiness Questionnaire (PAR-Q) (Thomas, Reading, & Shephard, 1992), and (6) not taking any medication.

At baseline, age and sex were self-reported by participants. Body mass index (BMI) was calculated as weight divided by height (kg.m^{-2}). Language-free intelligence was assessed by the Test of Nonverbal Intelligence (TONI-2), with internal test reliability varying from 0.81 to 0.98 and test–retest reliability ranging between 0.80 and 0.95 (Konter, 2010). Amount of physical activity was assessed using a Taiwanese version of the International Physical Activity Questionnaire (IPAQ) (Kelishadi et al., 2007; Liou, Jwo, Yao, Chiang, & Huang, 2008). Socioeconomic status (SES; assessed with the following five scales: 1, high social status; 2, medium to high social status; 3, medium social status; 4, medium to low social status; and 5, low social status) was assessed on the basis of parental education and occupation. All children were compensated $60 after completing the study.

2.2. Motor skill-based physical activity

The motor skill intervention occurred in an 8-week gymnastics program during weekend afternoons during the summer vacation. Children in the gymnastics group (N = 26) were divided into two sub-groups (N = 13 each). Each subgroup attended 2 sessions per week, with a duration of 90 min per session. The program was led by Physical Education teachers with more than 10 years of experience in gymnastics training. It consisted of movements involving interlimb gross motor movements that alternated between dynamic and static movements and involved a large range of movement, such as floor exercises, vaulting box, gymnastics trampoline, balance bean, walking in hurdles, and walking in crawl forward and backward on paralleled bars. We specifically focused on gross motor skills because a study (Beck et al., 2016) has indicated that individual differences in gross motor skills, but not fine motor skills, may partially account for individual differences in performance on cognitive-dependent measures (i.e., mathematics performance). The children were instructed to wear sporty clothes, have enough sleep the day before, and avoid consuming caffeine before training sessions. Each session began with a 15-min warm-up, followed by 65 min of gymnastic training, and then 10 min of stretching. In each session, two of the 13 children were randomly selected to wear a polar heart rate (HR) monitor to collect physical activity intensity data, (recorded by RS800CX Polar HR monitors; Polar Electro, Finland). Ratings of perceived exertion (RPE) were also measured every 10 min by using a Borg 6–20 scale (Borg, 1982; Bhammar, Stickford, Bernhardt, & Babb, 2017) in all 13 children. Mean HR and RPE were 136.4 ± 16.8 bpm (corresponding to 68% of age-predicted HR_{max}) and 11.8 ± 1.8, respectively, indicating that the gymnastics intervention corresponded to a moderate level of physical activity intensity. Children were asked to continue their routine of daily activities (e.g., school curriculum, extracurricular sports, or classes) when not attended the intervention.

Alternatively, children in the waitlist control group received no intervention and were instructed to maintain their routine of daily activities. They received access to the same gymnastics intervention after the study period. Logs of daily activities were recorded and provided by parents throughout the study period in both groups to ensure that all participants maintained their routine daily activities.

2.3. Measurements

Key measurements including motor competence, physical fitness, working memory assessment, and ERP recording were taken place before and after the 8-week intervention period. Test administers were blinded with group assignment to ensure both groups of children were equally motivated in performing these assessments.

2.3.1. Fitness assessments

The motor skill and physical fitness assessments served as manipulation checks to assess the effects of motor skill training. Motor skill was assessed by the second edition of the Movement Assessment Battery for Children (MABC-2). The MABC-2 (Henderson, Sugden, & Barnett, 2007) is an evaluative assessment tool that can be used to identify children's motor skills. The MABC-2 measures both fine and gross motor skills for children in three age groups (i.e., 3–6 years, 7–10 years, and 11–16 years). It contains eight tasks for each of the three age groups in three different constructs: manual dexterity, ball skills, and static and dynamic balance. The raw score for each task is converted to an age-adjusted standardized score, and a total test score is then calculated by summing the standard scores of the eight tasks. To standardize the total score, percentiles can be found from the age-adjusted norms published by the MABC-2 manual to determine a child's motor skill (Henderson et al., 2007).

Cardiovascular fitness was measured by a Progressive Aerobic Cardiovascular Endurance Running test (PACER, Human Kinetics, Champaign, IL). A 20-m endurance shuttle run was administered for measuring cardiovascular fitness, with higher number of completed laps indicative of better cardiovascular fitness (Hsieh et al., 2017).

The number of sit-ups within 60 s, standing broad jump, and sit-and-reach were administered for measuring aspects of muscular-related fitness. This test is a valid and standardized test for muscular fitness used with Taiwanese students from elementary school to college students. A description of these tests is as follows:

(1) Sit-ups (muscular endurance): Participants lay with their back on a cushion on the floor, with feet flat on the floor and knees bent at 90°. Participants crossed their arms over their chests so that their hands touched on the opposite shoulder. The trunk was then raised so as to touch the elbow to the patellae. The scores were recorded as the number of curl-ups completed in 60 s.

(2) Standing broad jump (explosive power): Participants stood behind the starting line with feet hip-width apart and bent knees. They swung their arms as they jumped, and the distance jumped was measured from the starting line to the heel closest to it. If the participant fell backward, the distance was measured from the starting line to the body part closest to it. The distance recorded was the best out of three jump attempts.

(3) Sit-and-reach (flexibility): Participants removed his/her shoes and sat down on the floor with legs stretched straight out. The soles of the feet were placed flat against the vertical 'sit-and-reach' ruler and both arms were extended forward along the measuring line as far as possible with their palms facing down. The distance from the fingertips to the edge of a ruler in centimeters was measured, and measurements were taken when the participants had held the extended position for at least two seconds. Further distances indicated better lower back and hip joint flexibility.

2.3.2. Delayed-matching working memory task

The procedure of the working memory paradigm is summarized in Fig. 1. The present study used a modified delayed-matching test, the same task employed in a previous study (Hsieh et al., 2017), to examine spatial working memory. Participants were administered this test before and after the intervention. Those administering the tests were blinded to group assignment to ensure equal motivation of all participants in performing this task. The task was programmed with STIM 2.0 software (Neuroscan Ltd., El Paso, TX). All stimuli were presented on a 17-inch computer monitor against a black background using STIM software (Neuroscan Ltd, El Paso, TX, USA) that was placed 60 cm in front of the participant. The paradigm was adapted from Hsieh et al. (2017) following similar procedures. Stimuli consisted of a red dot (0.5° × 0.5°) randomly positioned at any one of nine locations (i.e., center, center right, center left, upper center, upper right corner, upper left corner, lower center, lower right corner, and lower left corner) within a 3.8° × 7.4° gray rectangle. In each trial, the rectangles and red dot appeared following a 3-second or a 6-second delay. The first stimulus (S1) appeared on either the right or left side of a central fixation cross (0.5° × 0.5°) for 185 ms with equal probability. The S1 was followed by a delay of 3 s or 6 s, during which time participants were told to keep their attention fixed on the central cross. Afterwards, the cross was replaced by a second rectangle and red dot (S2) for 500 ms in the center of the screen. Participants were instructed to retain the position of the S1 red dot in memory during the 3 s or 6 s delay and then determine whether its position was identical to the position of the red dot in S2. Participants were instructed to press the ‘Yes’ key on a computer keyboard as quickly as possible if the position was consistent, or the ‘No’ key if it was inconsistent, using the index finger of both hand to response. Feedback was provided in the form for response accuracy following 2 s after the participant responded. The next trial then started 1000 ms later with the announcement of ‘next trial’. After achieving a 70% response accuracy threshold on the 20 practice trials, participants were then administered 6 blocks of 30 trials, resulting in a total of 180 trials (90 trials per memory condition). The order of the equiprobable 3-s interval and 6-s interval trials, which represented lower and higher working memory demands, were randomly presented within each block. Rest intervals of between 3 and 5 min were provided following each block, and longer rest intervals were allowed if necessary. Measures of response accuracy (i.e., accuracy rate over the total number of trials), mean RT for correct trials, and coefficient of variation of RT (CVRT) (i.e., the ratio of standard deviation of RT to mean of RT; represents intra-individual variability in RT, with larger CVRT signifying poorer response stability to S2) were used as performance outcomes.

2.3.3. EEG recording

Electroencephalographic (EEG) activity was recorded from 32 electrode sites using an elastic electrode cap (Quik-Cap; Compumedics Neuroscan, Inc., Charlotte, NC) according to the modified International 10–20 System. Scalp locations were referenced to linked mastoid (A1, A2) electrodes, whereas the ground electrode was attached to the mid-forehead (i.e., AFz) on the Quik-Cap, and additional electrodes were placed above and below the left orbit and the outer left and right canthi to monitor electrooculogram (EOG) activity with bipolar recording. All electrodes were maintained at impedances < 5 kΩ before data recording. Continuous data were digitized at a sampling rate of 1000 Hz, amplified 500 times with a DC to 200 Hz filter, and a 60 Hz notch filter using a Neuroscan Synamps 2 amplifier (Neuro, Inc., Charlotte, NC, USA).

The EEG data were filtered using a 0.1-Hz to 30-Hz band-pass cutoff (24 dB/octave), and the EOG activity was corrected using the algorithm from Semlitsch, Anderer, Schuster, and Presslich (1986). Epochs were created from −3385 ms to 0 ms (3 s condition) and −6385 ms to 0 ms (6 s condition) relative to S2 onset, baseline-corrected using the mean amplitude across the −3385 to −3185 ms and −6385 to −6185 ms window (200 ms before S1 onset) for 3 s and 6 s condition, respectively. Epochs with incorrect responses or an identified artifact which exceeded ± 100 μV were excluded. The mean numbers (mean ± SD) of epochs averaged are: pre-test 3 s: gymnastics group = 49.5 ± 12.9, waitlist group = 59.3 ± 12.8; pre-test 6 s: gymnastics group = 41.4 ± 11.4, waitlist group = 48.6 ± 11.5; post-test 3 s: gymnastics group = 60.2 ± 12.6, waitlist group = 57.7 ± 13.3; post-test 6 s: gymnastics group = 50.2 ± 11.6, waitlist group = 48.2 ± 12.6.

The iCNV was determined as the mean amplitude between the −2000 ms to −1500 ms and −5000 ms to −4500 ms time window relative to S2 onset for 3 s and 6 s conditions, respectively. The tCNV was

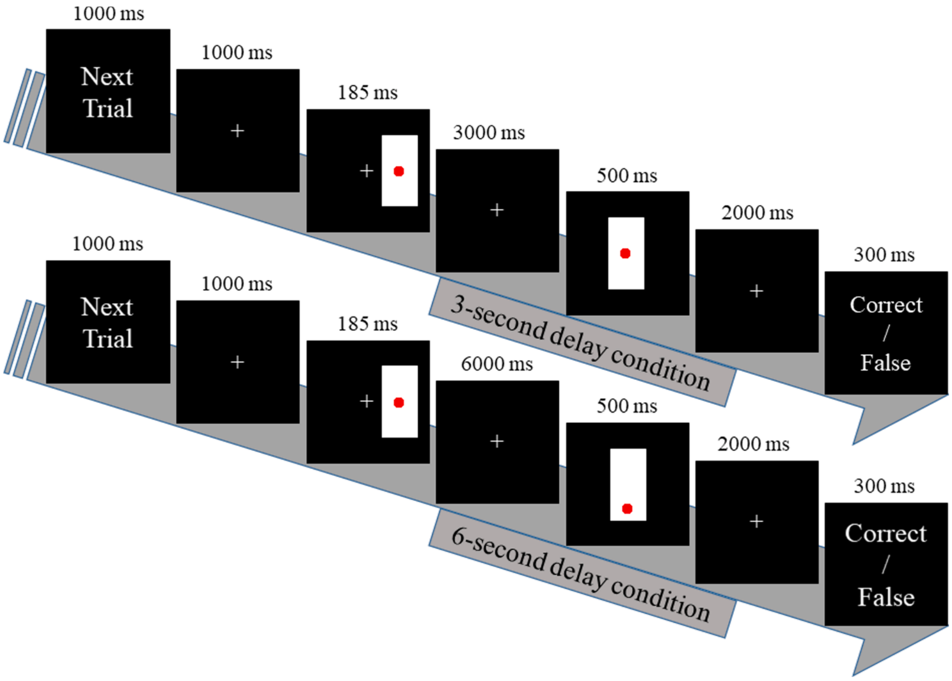

Fig. 1. Schemes of the working memory test. Participants first saw the encoding stimulus for 185 ms (S1), followed by a 3 s or 6 s delay period. Afterwards, a probe stimulus was presented for 500 ms (S2).

determined as the mean amplitude between the −500 ms to 0 ms relative to S2 onset for 3 s and 6 s conditions. These time windows were selected by referring to the grand-average waveforms (Fig. 2) and previous studies (Kamijo et al., 2011; Ludyga et al., 2018). Given that our preliminary analysis by collapsing data across interventions, time points, and task conditions revealed the largest (most negative) amplitude of iCNV and tCNV at Fz compared to other midline electrode sides, including FCz, Cz, CPz, and Pz (p's < 0.045), as well as a topographic distribution centered at the frontal regions (Fig. 3), Fz was selected for both CNV components. This decision could be supported by study who also focused on childhood physical activity and CNV (Kamijo et al., 2011).

2.4. Statistical analysis

Data on 2 children from the control group were discarded because they dropped out from the study for personal reasons. Therefore, data analyses were based on the remaining 50 children (26 children in the gymnastic group and 24 in children control group). Statistical analyses were performed using SPSS 23.0 software (IBM, inc.), with a family-wise alpha of 0.05. The normality of the data was confirmed using the Shapiro–Wilk test. For demographic data, independent t-tests were performed on age, BMI, IQ, physical activity, and SES, and a chi-square test was used for the sex distribution to ensure homogeneity between groups. For fitness performance, 2 (*Group*: gymnastics, control) × 2 (*Time*: pretest, post-test) repeated-measure analyses of variance (RM ANOVAs) were performed on subscores of M−ABC, total score of MABC, PACER, muscular endurance, explosive power, and flexibility. For behavioral performance, 2 (*Group*) × 2 (*Time*) × 2 (*Condition*: 3 s, 6 s) RM ANOVAs were used for response accuracy, RT, and CVRT, respectively. For CNV analyses, 2 (*Group*) × 2 (*Time*) × 2 (*Condition*) RM ANOVAs were performed on mean amplitudes of iCNV and tCNV collected from Fz. Greenhouse–Geisser corrections were used if the assumption of sphericity was violated. *Post hoc* comparisons were compensated for by using *Bonferroni*-corrected t-tests. Furthermore, to test whether changes in CNV related to changes in behavioral performance, Pearson product-moment correlations were performed between changes in behavioral measures (i.e., response accuracy, RT, CVRT) and CNV measures (i.e., iCNV amplitude, tCNV amplitude) in the gymnastics group wherever significant physical activity effects were detected. Data were obtained by subtracting pretest data from posttest data (post-pre). If there were multiple pairs of correlation to be tested (e.g., changes in RT, changes in accuracy, and changes in iCNV under the 3 s condition), *Bonferroni* correction would be applied to test whether the correlation was significantly different from 0.

3. Results

3.1. Demographic characteristics

Participants' demographic and fitness data are provided in Table 1. Demographic variables did not differ between the gymnastics and control groups (p's ≥ 0.080).

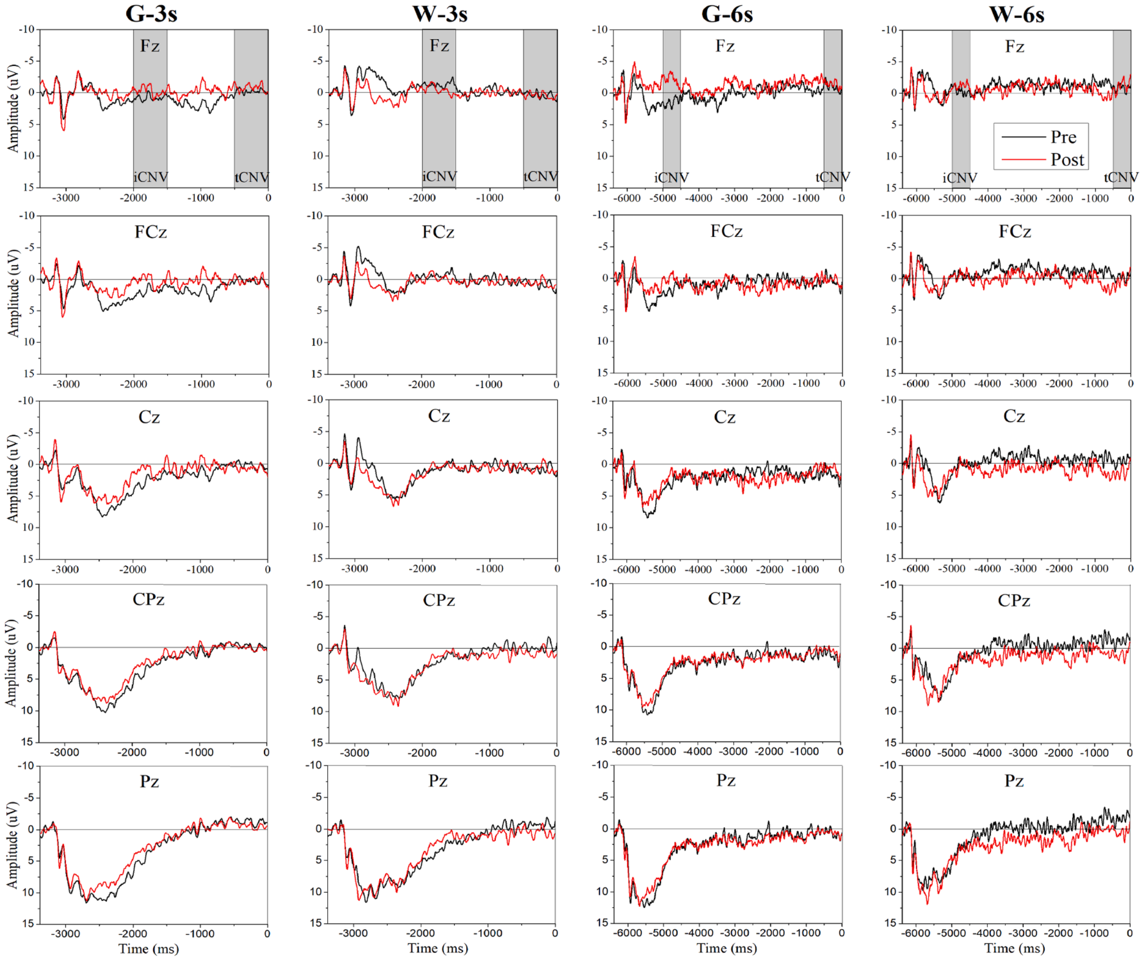

Fig. 2. Grand averaged event-related potential waveforms at midline electrode positions in 3 s and 6 s conditions. The latency ranges from −3385 ms to S2 onset (3 s condition) and −6385 ms to S2 onset (6 s condition) displayed for each group (G = gymnastics group; W = waitlist group) and the time point (Pre = pre-test; Post = post-test). Gray areas in Fz plots represent time windows of iCNV and tCNV.

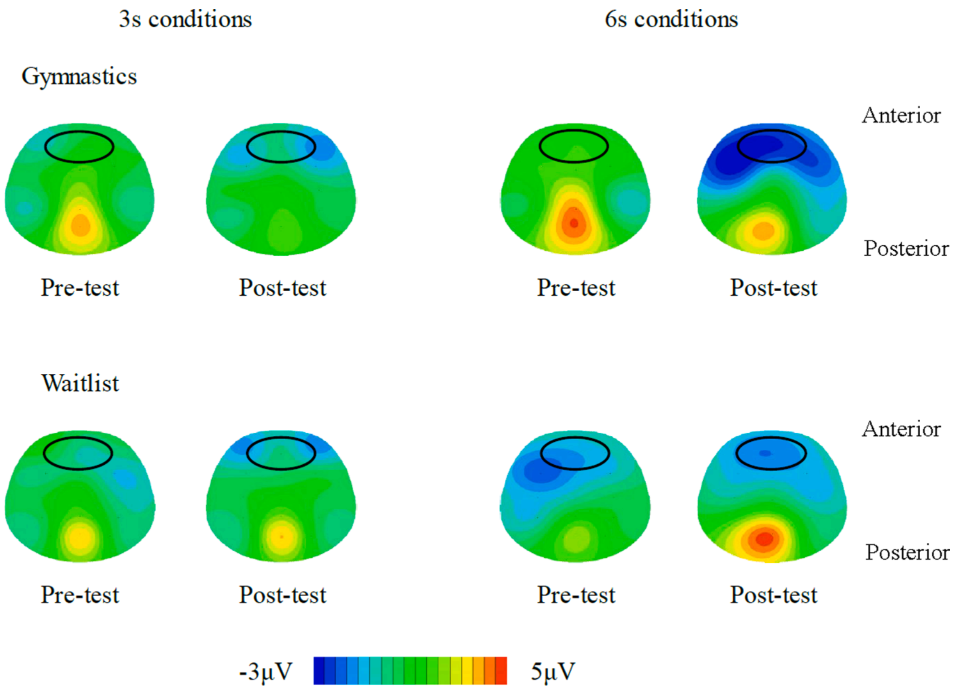

Fig. 3. Topographic distribution of iCNV (-2000 to −1500 ms relative to S2 for 3 s condition and −5000 to −4500 ms relative to S2 for 6 s condition) in the pre- and post-test. Topographic distribution of iCNV amplitude (spectrum: blue to red) is illustrated for the 3 s and 6 s conditions in the gymnastics group and waitlist group, respectively (G = gymnastics group; W = waitlist group) and the time point (pre = pre-test; post = post-test), with the frontal regions circled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mean (SD) values for participant demographics.

Variable	Gymnastics, M (SD)	Waitlist, M (SD)
Sex (M/F)	13 /13	13 /11
Age (years)	8.5 ± 1.1	8.7 ± 1.1
BMI (kg ⁄m^2)	16.8 ± 2.8	16.8 ± 1.8
IQ	107.1 ± 11.9	113.4 ± 13.1
Physical activity (METs)	1179.5 ± 761.3	1214.2 ± 1010.6
SES	2.3 ± 0.9	2.2 ± 0.8

Notes. BMI = body mass index; SES = socioeconomic status.

3.2. Fitness performance

For the MABC overall score, data analysis revealed a main effect of *Time* ($F_{1,48} = 15.28$, $p < .001$, $\eta^2_p = .24$). This main effect was superseded by a *Group* × *Time* interaction ($F_{1,48} = 9.75$, $p = .003$, $\eta^2_p = .16$). *Post-hoc* comparisons indicated a significant improvement only in the gymnastics group ($t(25) = 4.7$, $p < .001$).

As for manual dexterity, there was a significant main effect of *Time* ($F_{1,48} = 17.26$, $p < .001$, $\eta^2_p = .26$), with higher scores at post-test compared to pre-test in both groups.

Analysis of ball-handling indicated a main effect of *Time* ($F_{1,48} = 6.37$, $p = .015$, $\eta^2_p = .11$). This main effect was superseded by a *Group* × *Time* interaction ($F_{1,48} = 6.37$, $p = .015$, $\eta^2_p = .11$), with *post-hoc* comparisons showing a significant improvement only in the gymnastics group ($t(25) = 3.2$, $p = .003$).

There was a significant *Group* × *Time* interaction for the balance data ($F_{1,48} = 11.74$, $p = .001$, $\eta^2_p = .19$), with *post-hoc* comparisons only showing an improvement in the gymnastics group ($t(25) = 2.9$, $p = .007$).

For cardiovascular endurance (PACER), the results did not reveal any significant interactions or main effects (p's ≥ 0.837; p's ≥ 0.585).

A significant *Group* × *Time* interaction was found for muscular endurance ($F_{1,48} = 5.29$, $p = .026$, $\eta^2_p = .09$). *Post-hoc* comparisons showed a significant improvement only in the gymnastics group at post-test ($t(25) = 2.2$, $p = .032$).

There was a significant main effect of *Time* for explosive power ($F_{1,48} = 12.55$, $p = .001$, $\eta^2_p = .20$), and a significant *Group* × *Time* interaction was observed ($F_{1,48} = 10.61$, $p = .002$, $\eta^2_p = .18$). *Post-hoc* comparisons indicated significant improvement only in the gymnastics group ($t(25) = 4.7$, $p < .001$).

Analysis of flexibility revealed a main effect of *Time* ($F_{1,48} = 27.90$, $p < .001$, $\eta^2_p = .368$). The main effect of *Time* was superseded by a *Group* × *Time* interaction ($F_{1,48} = 45.74$, $p < .001$, $\eta^2_p = .488$), with *post-hoc* analyses indicated that flexibility at post-test was significantly better than at pre-test in the gymnastics group ($t(25) = 7.5$, $p < .001$); and at post-test, the gymnastics group was significantly better than the control group ($t(48) = 2.9$, $p = .005$). Table 2 summarizes results of the motor competence and physical fitness outcomes.

3.3. Working memory performance

Table 3 summarizes response accuracy, RT, and CVRT for each group and task condition. Analysis of response accuracy revealed a main effect of *Condition* ($F_{1,48} = 122.18$, $p < .001$, $\eta^2_p = .718$), with greater response

Table 2
Summary of fitness performance.

	Gymnastics, M (SD)		Waitlist, M (SD)	
	Pre-test	Post-test	Pre-test	Post-test
MABC-2				
Overall score	84.6 ± 10.1	93.2 ± 7.1*	89.3 ± 8.4	90.2 ± 10.9
Manual dexterity	33.1 ± 6.2	37.2 ± 4.5*	34.8 ± 3.4	36.7 ± 3.8*
Ball-handling	18.0 ± 4.6	21.0 ± 4.0*	20.1 ± 5.2	20.1 ± 6.3
Balance	32.9 ± 4.5	35.0 ± 2.3*	34.7 ± 2.3	33.4 ± 3.6
Physical Fitness				
Cardiovascular endurance (laps)	34.9 ± 2.8	35.0 ± 3.4	35.8 ± 3.9	36.0 ± 4.1
Muscular endurance (counts)	21.3 ± 10.3	24.1 ± 8.2*	26.8 ± 10.9	25.9 ± 10.6
Explosive power (cm)	124.3 ± 18.8	135.2 ± 16.7*	134.4 ± 22.3	134.9 ± 23.4
Flexibility (cm)	30.2 ± 8.0	35.6 ± 6.7*	30.5 ± 7.1	29.9 ± 6.9

Notes. Differ from pre-test; *$p < .05$.

Table 3
Summary of behavioral performance.

	Gymnastics, M (SD)			Waitlist, M (SD)		
	Pre-test	Post-test	Pre-Post change	Pre-test	Post-test	Pre-Post change
Accuracy (%)						
3 s conditions	66.3 ± 15.1	75.0 ± 13.8*	8.7 ± 11.3*	70.4 ± 12.5	72.0 ± 11.1	1.7 ± 14.4
6 s conditions	57.8 ± 12.2	64.5 ± 10.5*	6.7 ± 11.2*	60.2 ± 9.0	60.8 ± 8.9	0.6 ± 11.1
RT (ms)						
3 s conditions	1201.6 ± 166.9	1087.1 ± 189.1*	−114.5 ± 101.3*	1197.2 ± 114.9	1132.2 ± 125.6*	−65.0 ± 146.0*
6 s conditions	1210.4 ± 178.9	1083.2 ± 187.6*	−127.2 ± 104.6*	1214.6 ± 136.9	1138.4 ± 140.0*	−76.2 ± 136.7*
CVRT (%)						
3 s conditions	22.7 ± 4.0	22.3 ± 4.3	−0.4 ± 5.5	21.4 ± 3.0	20.7 ± 3.4	−0.7 ± 4.5
6 s conditions	22.4 ± 5.4	23.1 ± 4.8	0.6 ± 6.2	21.3 ± 2.7	22.4 ± 3.8	1.1 ± 4.2

Notes. *Differ from pre-test, $p < .05$; RT = reaction time; CVRT = coefficient of variation of reaction time.

accuracy in the 3 s condition compared to the 6 s condition; and a main effect of *Time* ($F_{1,48} = 10.60$, $p = .002$, $\eta^2_p = .181$), which is superseded by a significant *Group* × *Time* interaction ($F_{1,48} = 5.77$, $p = .020$, $\eta^2_p = .107$). *Post-hoc* analyses indicating that response accuracy at post-test was significantly better than pre-test only in the gymnastics group ($t(25) = 3.7$, $p = .001$) (Fig. 4).

For RT, a significant main effect of *Time* was observed ($F_{1,48} = 42.77$, $p < .001$, $\eta^2_p = .471$), with shorter RT at post-test compared to pre-test. No other main effect or interaction was observed (*p's* ≥ 0.092) (Fig. 4). As for CVRT, there was neither an interaction nor a main effect (*p*'s ≥ 0.066). (Fig. 4).

3.4. CNV

For iCNV, a significant main effect of *Time* was observed ($F_{1,48} = 6.29$, $p = .016$, $\eta^2_p = .116$). This main effect was superseded by a significant *Group* × *Time* interaction ($F_{1,48} = 5.27$, $p = .026$, $\eta^2_p = .099$). *Post-hoc* comparisons indicating larger mean amplitude at post-test compared to pre-test only in the gymnastics group ($t(25) = 3.0$, $p = .005$). Moreover, a significant *Condition* × *Time* interaction was also observed ($F_{1,48} = 10.66$, $p = .002$, $\eta^2_p = .182$), with *post-hoc* analyses indicating that mean amplitude at post-test was significantly larger than pre-test in the 6 s condition ($t(49) = 3.4$, $p = .001$). For tCNV, no interaction or main effect was observed (*p's* ≥ 0.056).

3.5. Bivariate correlations

Given the significant intervention effects on response accuracy and iCNV amplitude, Pearson product-moment correlations were performed between changes in response accuracy and changes in iCNV amplitude during the 3 s and 6 s conditions, respectively. Bivariate correlations indicated small to moderate correlations between changes in response accuracy with changes in iCNV in both task conditions (3 s condition: $r = -0.426$, $p = .030$; 6 s condition: $r = -0.435$, $p = .026$) in the gymnastics group, suggesting that greater improvements in response accuracy were associated with larger increase in iCNV.

4. Discussion

The purpose of the current study was to investigate the effects of a motor skill-based physical activity program on CNVs modulations and behavioral outcomes during a task that modulated working memory demands. To this end, an 8-week gymnastics program was implemented in children between 7 and 10 years old to investigate whether motor skill intervention affected neural and behavioral outcomes of working memory. Our main findings were that a) 8 weeks of gymnastics training facilitated response accuracy regardless of working memory demands, and b) a gymnastics program resulted in larger iCNV amplitude regardless of memory loads. Overall, the current study provides strong support for modulation in proactive control as a tangible neural maker underlies the beneficial effects of a motor skill-based physical activity program on working memory in children.

The behavioral findings indicated that while children in the gymnastics group improved their response accuracy, there was no such improvement among children in the waitlist control group. Further, our data revealed that a gymnastics intervention had generally facilitative effects on working memory performance regardless of task difficulty, which implies that children undergoing the gymnastics training were better able to maintain stored mental representations and accurately compare them with subsequently presented information regardless of memory demands. Such generally facilitative effects on working memory corroborate previous studies using either cardiovascular fitness-based intervention (Kamijo et al., 2011) or a combined cardiovascular and motor skill-based physical activity (Ludyga, Gerber, et al., 2018), suggesting that a variety of physical activity interventions improve childhood working memory regardless manipulations in memory capacity.

On the other hand, both children in the gymnastics and control groups had shorter RT following the intervention, which may be attributable to practice effects and/or task familiarization. However, it should be noted that, compared to response speed, response accuracy is often considered a more accurate behavioral measure in children given that they tend to act more impulsively, resulting in maintenance of response speed regardless of cognitive demands (Davidson, Amso, Anderson, & Diamond, 2006). To that end, we also observed no changes in CVRT as a function of intervention or time. Therefore, consistent RT changes across both groups does not detract from the observed improvements in response accuracy that was selectively observed following the gymnastics intervention.

One contribution of the current study is the expansion from our previous interventional study (Hsieh et al., 2017) by showing the modulatory effects of an 8-week gymnastics intervention on modulations in CNV sub-component amplitude during the encoding and maintenance of working memory. The current CNV findings couple with the behavioral findings, such that the gymnastics group exhibited larger (more negative) frontal iCNV from pre-test to post-test, whereas no intervention effect was found for the tCNV. The current findings, together with our recent published data (Hsieh et al., 2017), suggest that an 8-week gymnastic program improved neuroelectric outcomes, as signified by modulations in ERPs, during different phases of working memory in school-aged children. Previously, Ludyga and colleagues (Ludyga, Herrmann, et al., 2018) found a relationship between higher levels of motor skill and larger iCNV amplitude, but not tCNV, using a cross-sectional design. In their following 9-month longitudinal study, Ludyga et al. (in press) replicated such selective association. Importantly, the current study replicated their findings and moved one step further by showing that a gymnastics program may aid children in actively maintaining goal-relevant information during response preparation on working memory tasks. Moreover, the significant correlation between larger increases in iCNV amplitude and greater improvement in response accuracy in the gymnastics group implies that the iCNV might be a tangible neural marker for examining the effects of motor skill-

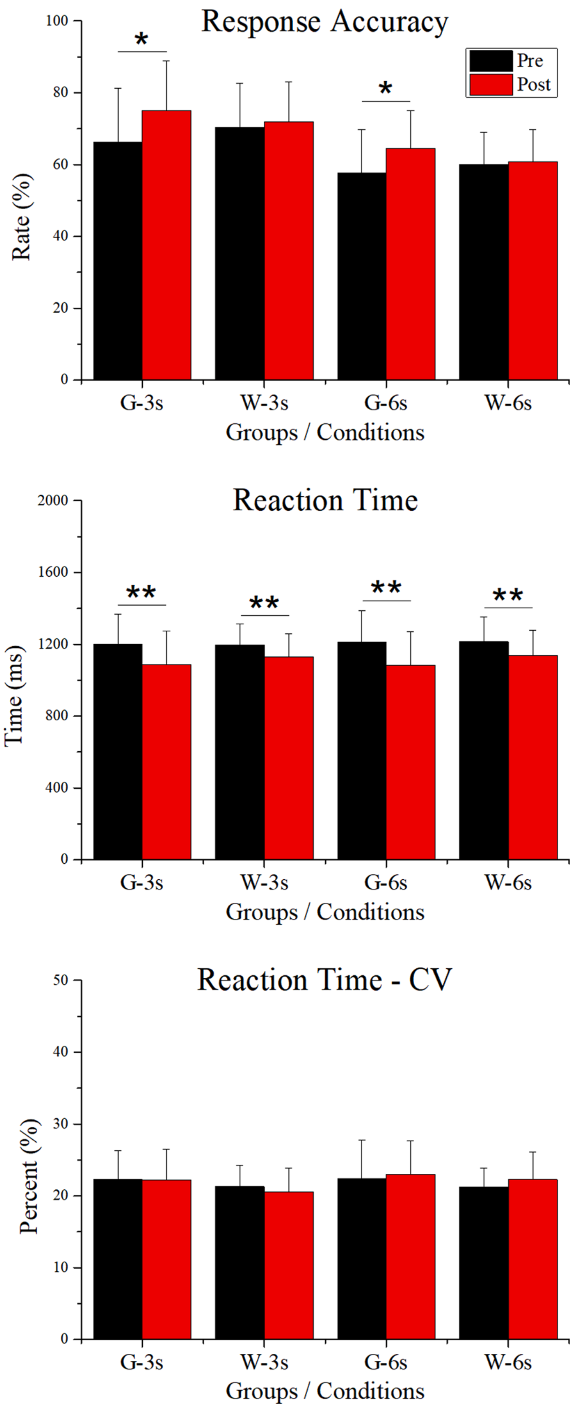

Fig. 4. Mean response accuracy, RT and CVRT at pre-test and post-test for each group (G = gymnastics group; W = Waitlist group). Data are presented as mean and SD; $^{*}p < .05$. $^{**}p < .01$. Data on mean response accuracy showed a Group × Time interaction across 3 s and 6 s conditions, with overall response accuracy at post-test better than pre-test only in the gymnastics group.

based physical activity on response preparation and proactive working memory during childhood. Given that modulation in iCNV could be mediated by co-activation of the prefrontal and parietal cortex (Srimal & Curtis, 2008), it is plausible that a motor skill-based physical activity may induce favorable functional changes in these brain regions in children, with complementary results in proactive working memory. Collectively, the current findings provide stronger support for the causal effects of motor skill-based physical activity on proactive control replying on prefrontal-parietal network during response preparation and working memory in children.

From a neurocognitive perspective, the positive influence of our gymnastics intervention on working memory and its neuroelectric outcomes might be accounted for, in part, by greater functional connectivity between brain regions within the frontal-parietal networks. Previous research in young adults indicated that 6 weeks of dynamic balance training induced stronger resting-state frontal-parietal connectivity (Taubert, Lohmann, Margulies, Villringer, & Ragert, 2011), suggesting the modulatory effects of motor skill training on functional connectivity in these brain regions. It is, therefore, worth investigating whether such modulatory effects on frontal-parietal connectivity could be found in a group of school children administering motor skill training, such as gymnastics, given that co-activation of these brain regions might occur when performing complex motor skills and working memory tasks (Anguera et al., 2010), and thus the '*rich*' physical activity intervention may activate both motor and cognitive components supported by this network.

There were several limitations to this study that should be acknowledged. First, as noted above, children in the gymnastics and control groups were recruited from separate regions (i.e., children in the gymnastics group were recruited from Yilan county, and children in the control group were recruited from Taipei city). One may argue that our findings were confounded by urban-suburban differences and should be interpreted with caution. However, data analyses revealed no group differences in any of the demographic variables collected (i.e., sex, age, BMI, IQ, physical activity, SES), suggesting that selection bias was not a major confounding factor. Moreover, given the close relation between motor competence and cognitive development during childhood as well as a lack of information on the effects of motor-enriched physical activity on neural substrates subserving the encoding and maintenance of working memory, the current study is novel in providing insights to the associations between childhood gymnastics, proactive control, and working memory despite a non-randomized design.

Second, the current study did not employ an active control group. Although debatable, there are issues associated with the use of an inactive, non-contact control group to compare against a physical activity group. However, as children in the control group were asked to maintain their typical daily routines, this group may best represent children's typical development. More specifically, the inactive, non-contact control group offers an opportunity to compare an intervention against typical development, which is not possible with an active control group. In this manner, an intervention that induces change in working memory over a period of time was compared with a group experiencing typical development. Thus, a non-contact control condition may serve as a 'moving target' for comparison in the current study.

Third, a related issue may be the lack of a cardiovascular-based intervention to compare against the motor-enriched intervention to minimize the confounding effects of subtle changes in cardiovascular fitness associated with the intervention. That is, one may argue that we were not able to delineate the specific aspects of the physical activity intervention (i.e., cardiovascular, motor, etc.) that led to improvements in working memory. However, since cardiovascular fitness did not change significantly in both groups, it seems unlikely that this fitness factor leads to the improvement of working memory in our sample. Despite this, it is still recommended for future study to implement both motor-enriched and cardiovascular-based interventions to have a more comprehensive view of the specific aspects of physical activity that result in improvement in working memory.

Fourth, it might be possible that social interactions around the physical activity, rather than the physical activity itself, driving the training-induced effects on working memory and iCNV. Nevertheless, research has indicated the superior effects of cognitively demanding physical activity intervention relative to active control intervention (e.g., typical school activities/curriculum) in improving on-task behavior in adolescents (Mavilidi et al., in press) and cognition in children (García-Hermoso et al., 2020), suggesting that cognitive and motor elements that are added on top of typical school activities, where social interactions are inherent, facilitate students' cognition. Accordingly, it could be postulated that improved working memory and its associated neuroelectric modulations in our study are more likely driven by improved motor skills and fitness, rather than social interaction inherent during intervention.

Lastly, the lack of follow-up tests precludes any conclusions being drawn about whether there were long-term, sustained effects of training. Given that chronic physical activity affects neural substrates underlying cognitive processing in children (Krafft, Pierce, & Schwarz, 2014), the physical activity-induced benefit may be sustained. In fact, a recent study (Beck et al., 2016) has reported a prolonged effect (i.e., 8 weeks after training cessation) of motor-enriched math lessons on spatial working memory in children. Nevertheless, this issue needs to be confirmed by further studies with follow-up measures.

In summary, the current study found that an 8-week motor skill-based physical activity intervention (i.e., childhood gymnastics) improved working memory and resulted in increased iCNV in children. Such findings provide stronger support for up-regulation of proactive control as a tangible neural maker characterizing the beneficial effects of motor skill-based physical activity on performance of tasks that modulate working memory demands in children. Given the close relation between increased motor skills and better working memory during childhood (Hsieh et al., 2017; Ludyga et al., in press), the predictive role of working memory for learning (Alloway, 2009; Engle et al., 1999), and that higher levels of childhood motor skill is one of the determinants of an active lifestyle during later adolescence and adulthood (Myer et al., 2015), the current findings highlight the potential of gymnastics as a viable option to schools seeking to implement extra-curriculum or after-school physical activity interventions to increase physical activity levels, improve health, and facilitate cognitive development and learning of children.

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Declaration of Competing Interest

There is no conflict of interest to report.

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