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Short, frequent physical activity breaks improve working memory while preserving cerebral blood flow in adolescents during prolonged sitting - AbbaH teen, a randomized crossover trial

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Abstract

Purpose Physical activity (PA) breaks during school lessons have been suggested as a promising strategy to improve working memory performance in children and adolescents. There is a lack of studies investigating the underlying physiological mechanisms of PA on cognition, especially among adolescents. This study aimed to investigate the effects of different types of short frequent PA on adolescents' cognitive task-related changes in cerebral blood flow in the prefrontal cortex (PFC) and working memory performance compared to prolonged sitting.

Methods In this randomized crossover study, adolescents visited the laboratory on three different occasions for 80-minute sessions of prolonged sitting interrupted by four breaks for three minutes of simple resistance training (SRA), step-up at a pre-determined pace (STEP), or remaining seated (SOCIAL). Before and after each session, cognitive task-related changes in cerebral blood flow (oxygenated-hemoglobin, Oxy-Hb) during working memory tasks (1-, 2-, 3-back tests) were measured using functional near-infrared spectroscopy in the PFC. Accuracy and reaction time were derived from the working memory tasks. Linear mixed-effect models were used to analyze the data.

Results A total of 17 students participated (mean age 13.6 years, 11 girls). Significant time x condition interactions were noted for Oxy-Hb in the most demanding working memory task (3-back), with a decrease following prolonged sitting in the SOCIAL condition compared to both the SRA (β 0.18, 95% CI 0.12, 0.24) and the STEP (β 0.11, 95% CI 0.05, 0.17). This was observed in parallel with improvements in reaction time following SRA (β -30.11, 95% CI -59.08, -1.13) and STEP (β -34.29, 95% CI -69.22, 0.63) although this was only significant for the SRA and no improvements in the SOCIAL condition.

Conclusion We found that short frequent PA breaks during prolonged sitting among adolescents can prevent the decrease in cognitive task-related changes in cerebral blood flow that occur following prolonged sitting. This was

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observed simultaneously with improvements in working memory, indicating that changes in cerebral blood flow could be one factor explaining the effects on working memory. Future studies should investigate the efficacy of implementing these PA breaks in schools.

Trial registration Retrospectively registered on 21/09/2020, ClinicalTrial (NCT04552626).

Keywords Adolescents, Physical activity, Cognition, Cerebrovascular circulation, Academic performance

Introduction

Adolescence is a critical developmental phase when higher cognitive functions, such as executive functions, are developed [1]. Executive functions are higher-order mental efforts and consist of three core components, inhibition, working memory, and cognitive flexibility [2]. Working memory is an important component of executive functions and is the capacity to store and manipulate information in mind [2]. Executive functions have been associated with physical and psychological health, and with academic achievements [2]. Considering the crucial nature of these skills and their sensitivity to acute environmental factors, as well as their association with academic achievements, strategies to support and preserve them during prolonged learning periods are needed, especially in the school setting. This is particularly important because previous studies have found that children are sedentary for approximately 70% of the time during a typical school class [3]. Breaking-up prolonged sitting in the classroom may be beneficial for both cognitive and physical health, although the results from previous studies are mixed.

One promising strategy to break up prolonged sitting in the classroom is incorporating physical activity, as a bout of physical activity may acutely improve executive functions (especially working memory) as previously reported [4]. Although in a younger age group (mean age 7.7 years), one study found that sitting was associated with better attention, whereas stepping was associated with faster but less accurate responses in a working memory task [5]. While another study in adolescents found that reducing sitting time during the school day by 50% and replacing it with light physical activity led to positive effects on cardiometabolic biomarkers, although no significant improvements were observed on the cognitive task [6]. The lack of improvement on cognitive performance may be owing to the type of physical activity performed. Beneficial effects have been seen following both resistance training [7] and aerobic exercise [8] on academic achievement and executive functions, respectively. However, studies investigating the effects of different types of physical activity bouts [9], compared to prolonged sitting conditions are limited. One study among adolescents found a bout of resistance exercise to improve inhibition, whereas a bout of aerobic exercise did not [7]. However, a study in adults found beneficial effects of short breaks of aerobic exercise on working memory performance, while no effect was observed following bouts of simple resistance activities using body weight [10]. Concerning the length of physical activity bouts, some evidence suggests that shorter bouts of physical activity yield greater improvements on cognitive outcomes, compared to longer bouts [11, 12]. This has also been found in the school setting, where a 5-minute bout of physical activity improved cognitive performance, while longer durations of 10–20 min did not [13].

With regards to physical activity intensity, an inverted U-shaped relationship has been suggested, where cognitive performance improves with increasing physical activity intensity, up to a certain point, then cognitive performance starts to diminish with further increases in physical activity intensity [14, 15]. However, the intensity threshold when cognitive performance starts to decline remains unclear. In a study involving children, moderate-intensity physical activity improved selective attention, while high-intensity activity showed no additional benefits over passive sitting, suggesting that moderate intensity would be more beneficial than high intensity [16]. However, it should be noted that the timing of post-cognitive assessments could affect the results. For instance, larger effect sizes have been observed following light and moderate physical activity when the post-measure was conducted immediately afterward. However, for higher intensities, larger effect sizes were observed when the post-test was performed with at least one minute lag from the activity [17].

As seen, there is some evidence regarding the acute effects of physical activity on cognitive outcomes, but there is a lack of studies investigating the underlying physiological mechanisms. One such mechanism is cognitive task-related changes in cerebral blood flow [15]. During a cognitive task, neural activation will trigger a regional increase in oxygenated hemoglobin (Oxy-Hb) to meet the increased metabolic demand required to solve the task [18]. Therefore, one hypothesis is that physical activity, which causes an increase in systematic circulation could influence these cognitive task-related changes in cerebral blood flow in the prefrontal cortex. An increase in oxygen supply could help the neurons meet the increased metabolic demand needed to solve the working memory task. Previous studies in adults have concluded that there is an increase in Oxy-Hb in the prefrontal cortex during physical activity [15]. Further, a study in older adults found increases in cerebral blood flow and cognitive function following physical activity [19], similar findings have been observed in children [20]. Nevertheless, not all studies have found an increase in cerebral blood flow. One study in adults showed that short breaks of brisk walking improved performance on the working memory task while a reduction in cerebral blood flow was observed. However, no effects were observed on either cognitive performance or cerebral blood flow following the simple resistance breaks [10].

The mixed results observed across studies may be attributed to variations in the type of physical activity interventions implemented, as well as differences in the cognitive outcome measures used. For instance, in the study involving older adults, the physical activity conditions were 15 min of brisk walking with or without a cognitive component [19], while the study involving children utilized a 15-minute bout of either treadmill exercise at a continuous pace of 90% of heart rate max or in intervals at different intensities [20]. These studies both used the Stroop test, which assesses inhibition, as a measure of cognitive performance. However, in the study involving adults, shorter bouts of physical activity were implemented (three minutes of either simple resistance exercise or brisk walking every 30 min over three hours) and employed a working memory task (n-back) to evaluate cognitive performance [10]. Although improvements in cognitive task performance were observed in all three studies discrepancies in task-related changes in cerebral blood flow response may arise from varying physical activity protocols or neural responses contingent on which aspect of executive functions are being assessed, or even the age group being studied. Furthermore, the timing of post-tests has been suggested to be crucial in assessing task-related changes in cerebral blood flow, as the duration of elevated cerebral blood flow following the physical activity, before returning to baseline, remains uncertain [21]. Consequently, further investigation is warranted to examine cerebral blood flow responses across different physical activity regimens and populations.

As seen, acute effects of moderate physical activity bouts on cognitive outcomes has been reported, however, these studies typically employ activities which are impractical for classroom settings (such as treadmill running or weight training). In a feasibility study, school staff emphasized the importance of readily available resources, such as videos offering brief physical activity breaks (1–5 min), which could be easily integrated into classroom [22]. Research on the effects of such physical activity breaks on cognitive performance or cerebral blood flow is limited, despite their potential acceptability also among inactive students.

In the school setting, brief bouts (5 min) of teacher-led physical activity at moderate intensity have shown to improve executive functions [13]. However, there is limited research on how short bouts of physical activity affect task-related changes in cerebral blood flow in a classroom setting. While Mazzoli and colleagues evaluated task-related changes in cerebral blood flow in a school setting, their study involved a six-week intervention with daily physical activity breaks [23]. Therefore, their findings may not be directly comparable to studies investigating acute changes in cerebral blood flow. Thus, more research is needed to explore the impact of short physical activity breaks, including those facilitated by videos, on cognitive performance and cerebral blood flow in a classroom setting, especially among adolescents. The aim of the current study was to investigate the effects of two types of short physical activity breaks (low intensity simple resistance training, or moderate intensity aerobic activity) during prolonged sitting, compared to continuous prolonged sitting on adolescents' working memory task-related changes in cerebral blood flow in the prefrontal cortex and working memory performance.

The primary research question was:

1. What are the effects of 80-minutes of prolonged sitting with and without short, frequent physical activity breaks (of low intensity simple resistance training or moderate aerobic activity) on prefrontal cortex cerebral blood flow measured during a working memory task?

The secondary research question was:

2. What are the effects of 80-minutes of prolonged sitting with and without short, frequent physical activity breaks (of low intensity simple resistance training or moderate aerobic activity) on working memory performance?

We hypothesize that:

a. There will be cognitive task-related increases in oxygenated hemoglobin (Oxy-Hb) following the conditions with physical activity breaks (both in the low intensity simple resistance training and moderate intensity aerobic activity) compared to the prolonged sitting condition, with a greater increase after the moderate intensity aerobic activity break.
b. There will be an improvement in cognitive performance (reaction time and accuracy on the n-back tests) after the physically active conditions (both low intensity simple resistance training and moderate intensity aerobic activity) compared to the prolonged sitting condition. The changes will

significantly differ between the conditions, such that more favorable changes will occur when the breaks are of moderate intensity.

Methods

Design

This study was a randomized study with a cross-over, pretest-posttest comparison design and three experimental arms. The study procedures are described in more detail in the protocol paper [24] and in the trial registration, retrospectively registered on 21/09/2020 at www.clinicaltrials.gov registration number: NCT04552626.

Students

Convenience sampling was used to recruit students in two schools in Stockholm, Sweden between September 15th, and October 26th, 2020. The inclusion criteria were students in grades 7 and 8 (13–15 years old). Exclusion criteria were ongoing infections or medication known to affect central and cerebrovascular circulation. Further, students unable to comprehend information regarding the study or the tests were excluded. The study was performed in a research laboratory at the Swedish School of Sport and Health Sciences, GIH, between November 2nd and December 16th, 2020, and no adverse events were reported. The students received a 600 SEK (€ 54) gift card as compensation for their participation.

Protocol

The students took part in a familiarization session before participating in the study. The session included an introduction to the study, submission of student and parental consent, a health questionnaire, and a practice of the cognitive test. Anthropometric measurements (weight and height), blood pressure, and head size measures (nasion-to-inion distance, distance between left and right preauricular points, and head circumference) for the functional near-infrared spectroscopy (fNIRS) cap (to ensure optimal fit) were also collected. After all the familiarization sessions were completed and the students were enrolled in the study by the research group, the allocation sequence for the order of experimental conditions was assigned through individual randomization from a computer-generated random order, equally assigned to every participant. Randomization was computer-generated by a researcher involved in the study and stored in a password-protected document. Researchers cannot be blinded in this type of study design or condition. Researchers within the study had access to the allocation sequence list and retrieved the randomization code before each experimental day to prepare the laboratory equipment [24]. A diagram of the participant flow can be found in Supplemental Fig. 2.

The students came to the laboratory on three experimental days. A washout period of at least six days between each visit was used to avoid any carry-over effect of the previous condition. In most cases, the students visited the laboratory during the same weekday and time for three consecutive weeks.

In the 24 hours preceding each experimental day, the students were asked to limit their physical activity and consume the same types of food and to avoid caffeine after dinner the night before. Their physical activity was monitored using a hip-worn accelerometer and a diary (with an integrated food and sleep log).

On each experimental day, the students were brought to the laboratory by taxi at the same time in the morning and were provided with a standardized breakfast (to minimize variations in physical activity and dietary intake between the experimental days).

An overview of the experimental session is provided in Fig. 1. Two students participated in each session. However, the students' start times were staggered by 20 min as the measurements were taken individually.

Each session began with a warm-up of the cognitive task, which included a shortened version of the cognitive test battery. This was performed to decrease a potential learning effect between the pre and post-tests.

Throughout the 80-minute session, the students were seated at a desk and asked to do schoolwork to simulate a classroom setting (computers were allowed). During this period four breaks (á 3 min) were performed every 17th min. The type of break varied between the three experimental conditions:

Social Students remained seated and chatted with a research staff member. This condition aimed to replicate an extended period of sitting, such as an 80-minute class, and to balance the time for social interaction between conditions.

SRA Students participated in simple resistance activities (SRA): three sets of half-squats, calf raises, and gluteal contractions, following a standardized video (inspired by [25]). The exercises were performed for 20 s each, using body weight. This physical activity break was selected for its ease of implementation in a classroom environment and its accessibility, regardless of students' or teachers' prior experience with resistance training. This choice was informed by previous research implementing the same video protocol among inactive adults [25], and was meant to simulate a low intensity resistance exercise break.

Step Students performed step-up on a standardized stepping height (27.5 cm) at a pre-determined pace of 110 beats per minute, following a standardized video. This physical activity break was chosen as it is easy to imple-

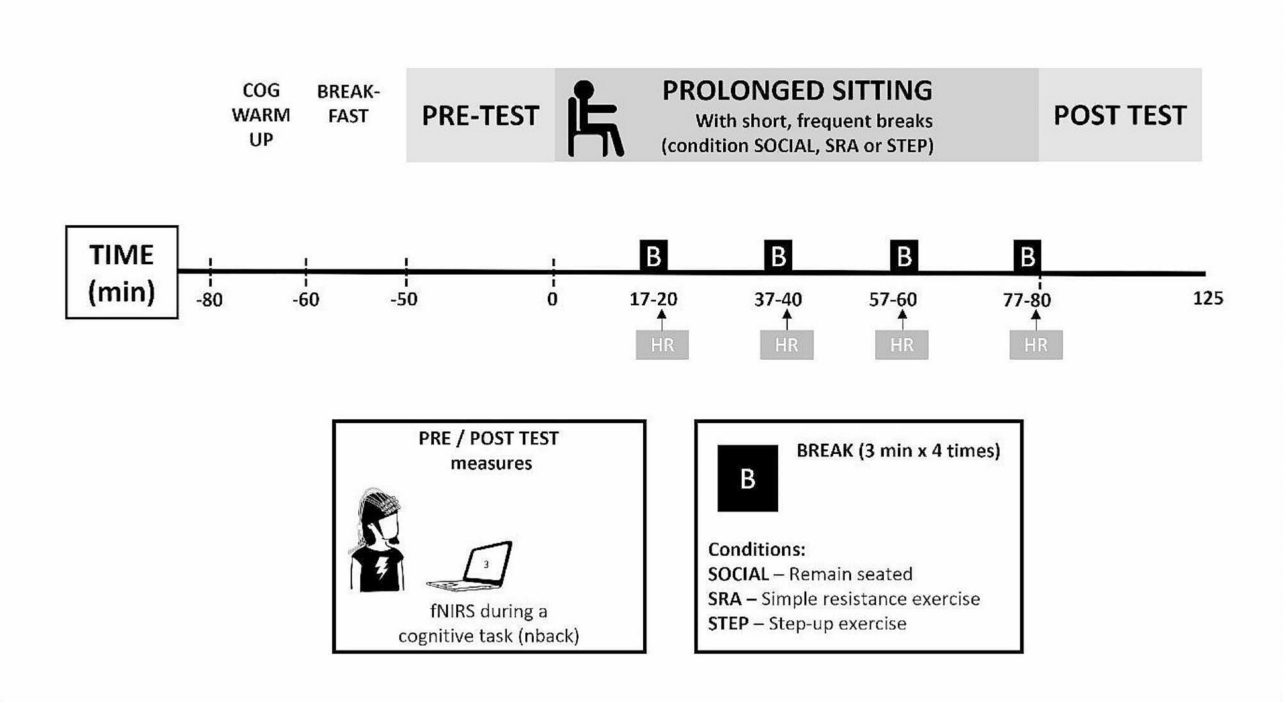

Fig. 1 Overview of the experimental session. The SOCIAL condition included 80 min of prolonged sitting with a 3-minute social break every 17th minute, the SRA condition included 80 min of prolonged sitting with a 3-minute simple resistance exercise every 17th minute, and the STEP condition included 80 min of prolonged sitting with a 3-minute step-up exercise every 17th minute. fNIRS: functional near-infrared spectroscopy

ment in classroom settings (requiring minimal space and prior skills of the students or teacher) and it was intended to replicate a moderate-intensity aerobic exercise break. At the end of each break, the student's heart rate was measured using a heart rate monitor with a chest strap (Polar Electro CE0537). Following the physical activity breaks the students were also asked to rate perceived exertion using the Borg scale [26].

Immediately before and after the 80-minute session, pre/post measurements were collected. Cognitive task-related changes in Oxy-Hb were measured in the prefrontal cortex using an fNIRS instrument while the students performed the working memory tasks (n-back).

Sample size

As described in the protocol paper [24], a sample size of 6–13 students was estimated using the G*Power software (Franz Faul, Universität Kiel, Germany, v 3.1.9.2) using data from studies with older populations [27–32]. The sample size was to ensure effect sizes between 0.9 and 2.4 on the primary outcome (changes in Oxy-Hb). As the calculation was based on older populations, 17 students were included in the current study to allow variance within the age group.

Measures

Cognitive task-related changes in cerebral blood flow

Changes in Oxy-Hb and deoxygenated hemoglobin (DeOxy-Hb) in the prefrontal cortex were measured during the working memory tasks using an fNIRS instrument (portable NIRSport, 8–8 system, with short-separation channels, NIRx Medizintechnik GmbH, Berlin, Germany).

This non-invasive method uses near-infrared light to estimate the change in Oxy-Hb and DeOxy-Hb through channels mounted on fNIRS caps placed on the student's head (see Fig. 2). The technique is based on the theory of neurovascular coupling; assuming that with neural activation (e.g., a cognitive task) the increased metabolic demand causes an increase in Oxy-Hb and a decrease in deOxy-Hb to the neurons in the specific region [18]. In the current study, 16 channels (8 LED light sources and 8 detectors; 3 cm apart; Si Photodiode) were placed across the prefrontal cortex (according to the standard 10–20 system), as this region typically is activated during a working memory task [2].

The data were sampled at 7.81 Hz at wavelengths 750 nm and 820 nm. To account for the superficial blood flow in the cortex 8 additional detectors of short-separation (0.8 cm) (NIRx Medizintechnik GmbH, Berlin, Germany) were used.

During the measurements, the cap was placed 2 cm above the nasion point and centered on the Cz. The light

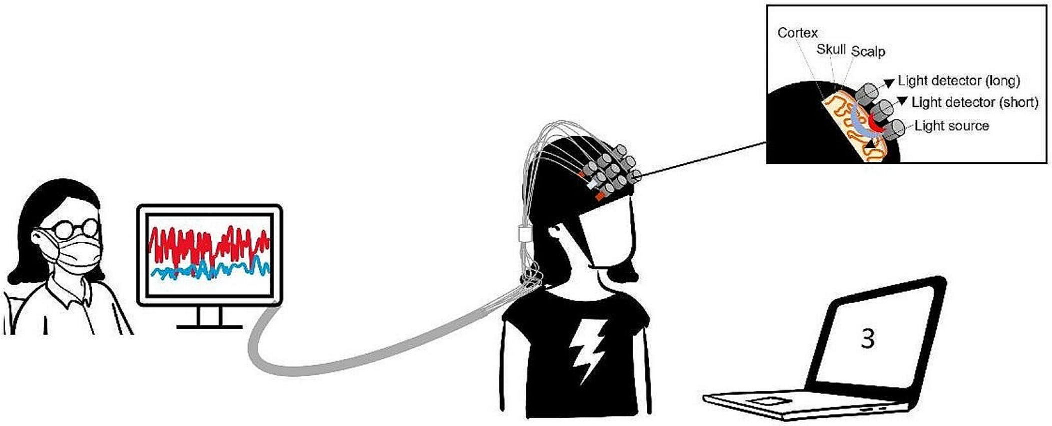

Fig. 2 fNIRS set up during the cognitive task (n-back). The fNIRS cap contains 16 optodes; 8 light sources, which emit near-infrared light into the prefrontal cortex, and 8 light detectors (3 cm apart). Short fiber detectors (0.8 cm) measure the superficial flow whereas long fiber detectors with a deeper penetration depth measure the hemodynamic response in the cerebral cortex

was dimmed in the laboratory and the students were provided with headphones to minimize any outside distractions. A system calibration was performed, and the quality of the signal was visually checked before and during the test to note any motion artifacts or loss of channels.

Working memory performance

Working memory was measured using a computerized n-back test (an overview is presented in Supplemental Fig. 1). The test was created in E-prime 2.0 (Psychology Software Tools) and included three mental loads, 1-, 2- and 3-back tests. The student was shown a digit on the screen and was asked to press a key to indicate if the digit shown was identical or not to the digit shown 1 stimulus previously (1-back), 2 stimuli previously (2-back), or 3 stimuli previously (3-back). A total of 3 blocks were performed per test session (pre and post) with each block consisting of 60 digits (20 per mental load). The variables of interest were accuracy (number of correct answers) and reaction time of correct answers (milliseconds, ms) as an average of the 3 blocks per mental load.

As an explorative analysis, a grouping variable for working memory performance was calculated using the pre-values for each condition. The students were ranked based on their task performance (accuracy or reaction time) on each mental load (1-, 2-, 3-back) during the pre-tests. Based on the rank, the students were dichotomized into two equally large groups (above and below median in accuracy or reaction time). One grouping variable was used for stratified analysis of the fNIRS data; based on the students' ranking in reaction time averaging all 3-back pre-tests.

Student characteristics

Bodyweight and height were measured, and results were rounded to the nearest 0.1 kg or mm. Body mass index (BMI) was calculated using body mass (kg), divided by height (m) squared. Further, a BMI standard deviation score (accounting for age and gender) was calculated using Karlberg et al., 2001 [33].

Self-reported gender, age, and weekly physical activity habits were reported. The students reported which days they participated in physical activity, duration, and type (i.e., organized sports, physical education class, or other). Total time in self-reported physical activity was calculated by summing up the total time during the week.

Physical activity, sleep, and dietary intake (24 h before each experimental day)

Time and proportion of time spent in moderate-to-vigorous physical activity (MVPA), light physical activity, and sedentary were measured using an accelerometer (Actigraph GT3X). The students were asked to wear the accelerometer on their hip at all waking time (except during water-based activities) during the day preceding the test days. The students recorded when they had worn the accelerometer, and an individual time filter was created based on these times. Raw acceleration was measured at 30 Hz. Data were processed in Actilife (v6.13.3) as uniaxial data with 5-second epoch time intervals. Non-wear time was defined as 60 min of zero count (no spike tolerance). The data were classified into intensities using counts and the following cut-offs: sedentary (0-100 counts/minute), light physical activity (101–2295 counts/minute), and MVPA (≥2296 counts/minute) [34].

Sleep was self-reported using a diary, and the students were prompted to answer the following questions within one hour of waking: "Which time did you go to bed last night?" and "Which time did you wake up?". Based on the reported sleep, duration was calculated.

Dietary intake was self-reported using the same diary, the students were asked to record all foods and drinks they consumed and asked to not consume anything except water after dinner.

Statistical analysis

Descriptive statistics of the students' characteristics and working memory performance are presented using means and standard deviations (SD) for normally distributed data, or medians and interquartile ranges (IQR) for skewed data. Repeated measures ANOVA was performed to examine the mean differences in heart rate and perceived exertion between conditions as well as mean differences in sleep and accelerometer-based physical activity patterns during the 24 h before each experimental day. Statistical significance was set at $p<0.05$, using a two-tailed test.

Cognitive task-related changes in cerebral blood flow

Relative changes in Oxy-Hb and DeOxy-Hb (Δμmol) were estimated using MATLAB-based software NIRS Brain AnalyzIR Toolbox (https://github.com/huppertt/nirs-toolbox [35]. Oxy-Hb was the predominant cerebral blood flow outcome as it has previously been reported to be the most sensitive indicator of neural activation [36, 37], DeOxy-Hb is reported in the supplemental material for reference. Raw intensity light was converted to optical density and subsequently to hemoglobin concentrations using the modified Beer-Lambert law [35]. Minimal manipulation was performed on the signals as suggested by Santosa et al. [35]. First-level statistics involved estimating the fNIRS parameters during the 1-, 2-, and 3-back tasks (each 35-sec duration) relative to the 20-sec rest. Brain activation was predicted using a general linear model (GLM) with a canonical design matrix (peak at 6 s, stimuli duration 35 s), with an age-adjusted differential path length factor as suggested by Scholkmann and Wolf [38]. To deal with motion correction and the unique characteristics of the fNIRS signals (due to the high serial correlations and heavy-tailed noise), an autoregressive pre-whitening approach with iteratively reweighted least squares (AR-IRLS) was used for each source-detector pair. The AR-IRLS approach helps to reduce the false-discovery rate. Short-separation regressors were included in the models to control for systemic physiology and motion artifacts. The GLM yielded regression coefficients (betas) for each channel in each n-back task and condition that was used in the second-level analyses (group-level analysis). The coefficients of ΔOxy- and ΔDeOxy-Hb each were averaged across the prefrontal region, and separately by left and right prefrontal hemispheres for each n-back task and condition. The Benjamini-Hochberg procedure was applied to deal with multiple comparisons (*q-value*=FDR-adjusted $p\leq0.05$). Linear mixed effect models were employed with ΔOxy- and ΔDeOxy-Hb as dependent variables, with condition and time as fixed effects and subject as a random effect to assess within and between condition differences in cerebral blood flow parameters during each n-back task. Changes from the pre-test to the post-test, for each n-back test and condition were separately assessed as well as contrasts between 2-back and 3-back relative to the 1-back test. Additionally, linear mixed-effect models were performed to assess intervention effects including time and condition as interaction terms.

Working memory performance

Working memory performance (accuracy and reaction time in the 1-, 2-, and 3-back tests) were analyzed in Stata (version 17; StataCorp LLC, College Station, TX) using linear mixed effect models, modeling the individual as a random effect to assess the within-person changes between pre-and post-test. Further, time-by-condition interactions were run to explore the effect of the intervention. The outcomes were checked for normality and the accuracy and the assumptions for mixed models were checked. As the assumption of normality was violated in some models, robust estimates were used. Effect sizes were calculated based on the mean change between pre and post for each condition using Cohen's d. Effect sizes above 0.5 were considered moderate, and above 0.8 as high [39]. Explorative analyses were performed to investigate if working memory performance (during the pre-test) moderated the intervention effect. This was done by adding an interaction term in the models, if the interaction was significant, stratified analyses were performed.

Results

A total of 17 students participated in the study, the sample characteristics are described in Table 1. The sample had an average BMI of 19 kg/m^2 (underweight $n=3$, normal weight $n=13$, overweight $n=1$), 65% were girls and 77% participated in organized sports. There was no

Table 1 Descriptive characteristics of the study sample by gender (mean ± SD unless otherwise specified)

	All	Girls	Boys	Sig *p*
Demographics	$n=17$	$n=11$	$n=6$	
Students, n (%)	17 (100)	11 (64.7)	6 (35.3)	
Age (year)	13.6 ± 0.7	13.9 ± 0.2	13.2 ± 0.2	**0.044**
Physiological characteristics				
Weight, kg	48.9 ± 7.2	49.8 ± 5.9	47.1 ± 9.42	0.477
Height, cm	160.8 ± 8.8	162.7 ± 7.5	157.4 ± 10.6	0.249
BMI, kg/m^2	18.9 ± 2.1	18.8 ± 1.8	18.9 ± 2.8	0.917
BMI standard deviation score	-0.10 ± 1.1	-0.18 ± 0.9	0.04 ± 1.4	0.709
Physical activity (self-reported)				
Weekly physical activity (minutes)	292.8 ± 126.6	293.5 ± 131.5	291.7 ± 130.3	0.979
Weekly physical activity (hours)	4.9 ± 2.2	4.9 ± 2.2	4.9 ± 2.2	0.979
Participated in organized sports, n (%)	13 (76.5)	8 (72.7)	5 (83.3)	0.622

SD: standard deviation, BMI: body mass index

Table 2 Physical activity and sleep duration during the 24 h before each experimental day (mean ± SD unless otherwise specified)

Condition	SOCIAL	SRA	STEP	Sig *p*
Physical activity (accelerometer)	$n=17$	$n=17$	$n=17$	
Wear-time (min)	842.4 ± 70.9	856.2 ± 76.5	825.3 ± 106.2	0.227
% in sedentary	77.0 ± 7.9	79.6 ± 5.5	78.0 ± 5.3	0.090
% in light	17.2 ± 6.2	14.5 ± 3.8	16.6 ± 3.9	**0.009**
% in moderate	3.6 ± 1.5	3.6 ± 1.2	3.4 ± 1.2	0.799
% in vigorous	2.1 ± 1.6	2.3 ± 2.4	2.1 ± 1.7	0.794
% in MVPA	5.7 ± 2.9	5.9 ± 3.2	5.4 ± 2.8	0.769
Total time in MVPA (min)	47.6 ± 23.6	49.4 ± 21.4	44.3 ± 23.1	0.647
Total time in light (min)	143.4 ± 47.5	123.3 ± 33.7	137.0 ± 35.9	**0.030**
Total time in sedentary (min)	651.4 ± 101.3	683.5 ± 90.6	644.0 ± 98.5	0.052
Sleep (self-reported)	$n=17$	$n=17$	$n=17$	
Sleep duration (hours)	8.0 ± 0.9	8.0 ± 0.8	8.1 ± 0.8	0.908

SD: standard deviation, SOCIAL: Social activity break condition, SRA: Simple resistance activity break condition, STEP: Step-up activity break condition, MVPA: moderate-to-vigorous physical activity

significant difference between boys and girls, except for in age.

Table 2 shows the students' accelerometer-based physical activity and sleep patterns the day before each condition. There were no significant differences in time spent in MVPA or sedentary between the conditions. However, the students spent significantly less time in light physical activity the day before the SRA condition.

The average heart rate of the breaks was 85±12 bpm during the SOCIAL condition, 115±16 bpm during the SRA, and 157±14 bpm during the STEP. The heart rates correspond to 57% of age-predicted heart rate max in the SRA condition and 79% in the STEP [40] (which is equivalent to light and high intensity). Further, the students rated their perceived exertion as 12±2 during the STEP and 9±2 during the SRA on the Borg scale, which corresponds to light and moderate physical activity, respectively. Heart rate and perceived exertion were significantly different between all conditions ($p<0.001$).

Cognitive task-related changes in cerebral blood flow in the prefrontal cortex

In total, 16 students had complete data for all conditions and were included in the Oxy-Hb analysis (one student was excluded due to technical issues during one of the measurements). The results are presented in Fig. 3 as change in Oxy-Hb between the pre-and post-test during the 2- and 3-back tests for each condition relative to the 1-back in the whole prefrontal cortex (and stratified by right and left hemispheres in Supplemental Table 1 along with deOxy-Hb results).

There were no significant changes in Oxy-Hb during the 2-back in any of the conditions. In the 3-back a significant decrease was noted for the SOCIAL condition, whereas a significant increase was seen following the SRA in the 3-back. There were no significant changes during the STEP condition for any of the n-back tests. A significant intervention effect was found during the 3-back. The 3-back change in the SOCIAL was significantly different from the change in SRA (β 0.18; 95% CI 0.12, 0.24; $q<0.001$), and the change in the STEP condition (β 0.11; 95% CI 0.05, 0.17; $q<0.05$).

Changes in working memory performance

All students had complete data for the working memory performance and were included in the analyses for all three conditions ($n=17$), pre- and post-values for working memory performance can be found in Supplemental Table 2. A significant improvement in accuracy was found only in the 1-back following the SOCIAL condition. For reaction time, significant improvements (faster reaction times) were seen in the 1-back and 2-back following SOCIAL. During the 1-back, these changes were significantly different from the SRA condition (β 38.03; 95% CI 2.34, 73.71; $p=0.04$). Further, significant improvements in reaction time were also found in the SRA during the 2- and 3-back tests and approaching significance in the STEP ($p=0.05$) for the 3-back. No significant intervention effects were found for accuracy or reaction time.

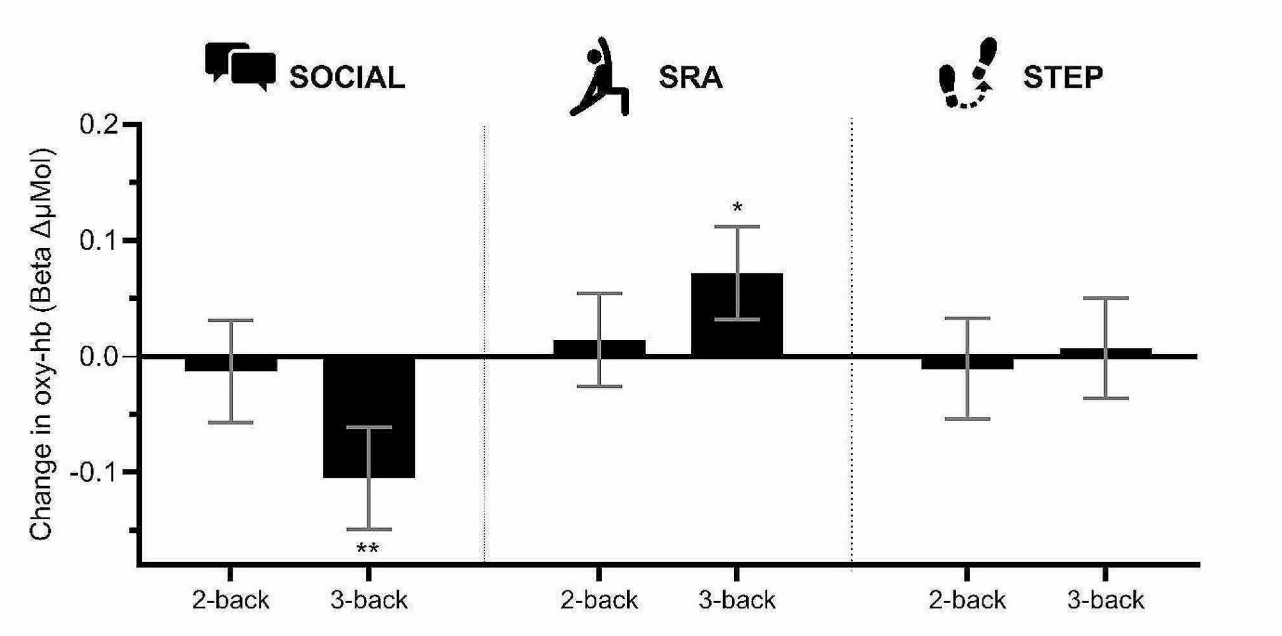

Fig. 3 Changes in oxygenated hemoglobin (Oxy-Hb) from pre-test to post-test in the 2-back and 3-back tests relative to the 1-back in the whole prefrontal cortex within each condition. **q < 0.05; **q < 0.01 for statistical significance after adjusting for multiple comparisons. SOCIAL: Social activity break condition, SRA: Simple resistance activity break condition, STEP: Step-up activity break condition*

These results can be found in Fig. 4 and Supplemental Table 3.

The largest effect sizes (Cohen's *d*) were found in reaction time. In the 1-back, moderate to large effect sizes were found when comparing the STEP and SOCIAL (*d* = -0.78; 95%CI -1.48, -0.08) and the SRA and SOCIAL (*d* = -0.80; 95%CI -1.50, -0.10). During the 3-back moderate effect sizes were seen between STEP and SOCIAL (*d* =0.63; 95%CI -0.07, 1.31) and SRA and SOCIAL (*d*=0.62; 95%CI -0.07, 1.30). All the effect sizes are presented in Supplemental Table 4.

Effect modification by baseline working memory performance

Working memory The moderating effect of baseline working memory performance on change in working memory performance between pre-test and post-test was also explored. In the SOCIAL condition, a significant moderating effect was found in accuracy (β -2.89; 95% CI -5.02, -0.76; $p=0.01$) and reaction time (β -54.35; 95% CI -92.24, -16.46; $p=0.01$) during the 1-back and in accuracy (β -5.70; 95% CI -8.77, -2.63; $p<0.001$) in the 2-back, such that those with baseline performance below the median showed larger improvement compared to those with performance above the median.

For the physical activity breaks, a moderating effect was found during the 1-back following the SRA (β -4.09; 95% CI -7.32, -0.85; $p=0.01$), with significant improvement in those below the median. In the STEP condition, a moderating effect was found during the 3-back in both accuracy (β -7.07; 95% CI -9.99, -4.15; $p<0.001$), and reaction time (β -44.58; 95% CI -81.32, -7.83; $p=0.02$), with greater improvements in the below-median group. For accuracy, the above-median group performed significantly worse after the STEP condition (stratified results can be found in Supplemental Figs. 3–4).

Cerebral blood flow Cognitive task-related changes in Oxy-Hb results stratified by baseline working memory performance can be found in Fig. 5 and Supplemental Table 5. Overall, no significant effects were found for the above-median group. In the below median group, a significant decrease in Oxy-Hb was seen following the SOCIAL condition during the 3-back, while in the SRA condition, a significant increase was found. No significant changes were found in the STEP condition. Further, intervention effects were found in the below-median group in the 3-back, where the changes following the physical activity breaks were significantly different from the prolonged sitting with an increase following the SRA (β 0.272; 95% CI 0.188; 0.356; $q<0.001$) and a small decrease following the STEP (β -0.135; 95% CI, -0.221, -0.050; $q<0.05$).

Discussion

In this study, we investigated the effects of 80-minutes of prolonged sitting with and without short, frequent physical activity breaks on cognitive task-related changes in cerebral blood flow in the prefrontal cortex and working memory performance. During the most difficult working memory task (3-back), a significant intervention

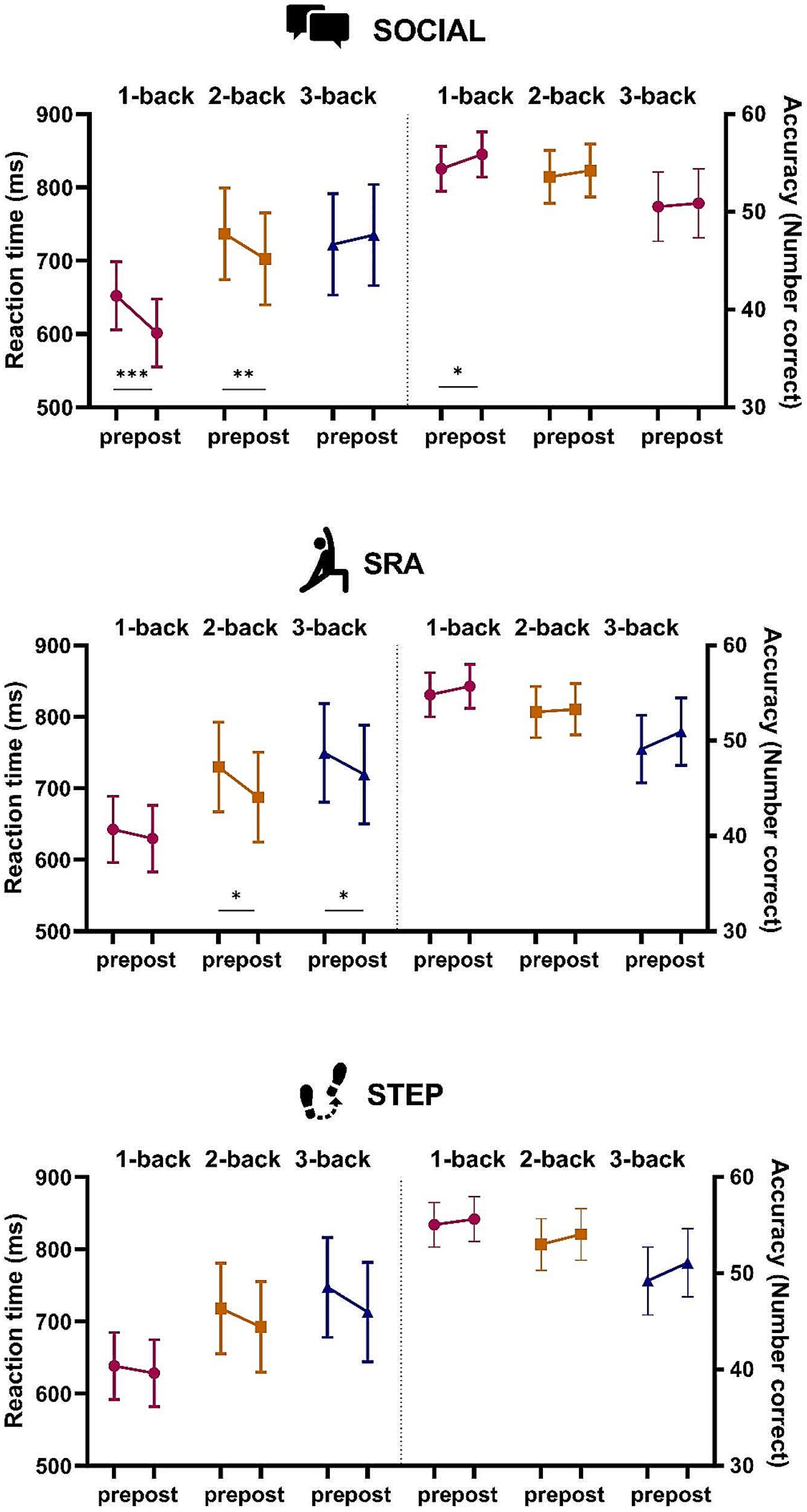

Fig. 4 Changes from pre-test to post-test in reaction time and accuracy within each condition for the 1-, 2-, and 3-back tests. **p* < 0.05; ***p* < 0.01; *** *p* < 0.001 SOCIAL Social activity break condition, SRA Simple resistance activity break condition, STEP Step-up activity break condition

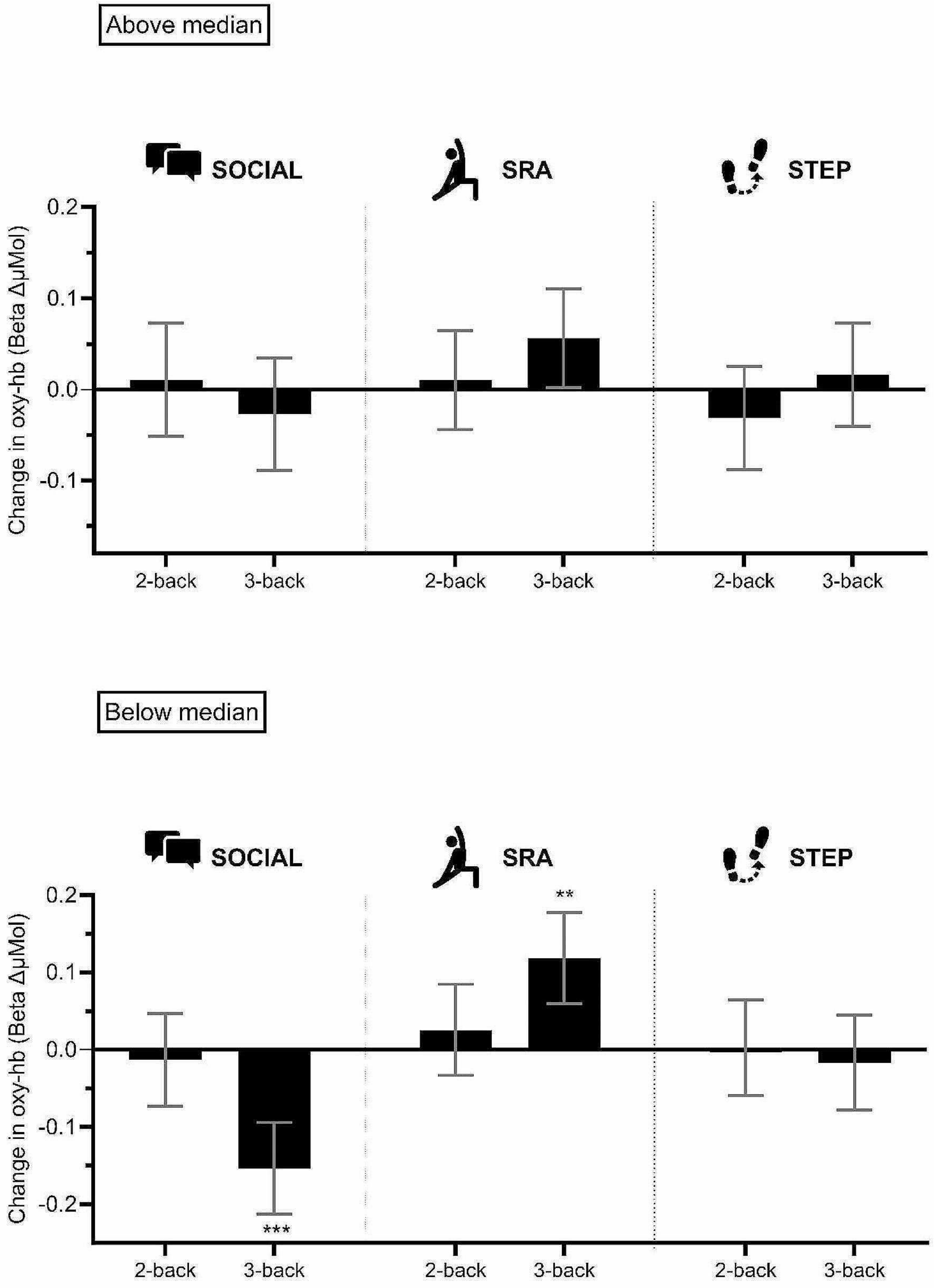

Fig. 5 Change from pre-test to pos-ttest in oxygenated hemoglobin (Oxy-Hb) during the 2-back and 3-back tests relative to the 1-back in the whole prefrontal cortex, stratified by baseline working memory performance using median split. **q < 0.01 *** q < 0.001 for statistical significance after adjusting for multiple comparisons *SOCIAL Social activity break condition, SRA Simple resistance activity break condition, STEP Step-up activity break condition*

effect was found, as the changes in Oxy-Hb were significantly different between the prolonged sitting condition (decrease in Oxy-Hb) and the physical activity break conditions (increase in Oxy-Hb). These changes occurred in parallel with improvements in reaction time on the working memory task, although these were only significant in the SRA. These changes were in line with our hypothesis, although we had hypothesized greater positive changes following the STEP condition, which was performed at moderate intensity.

We had hypothesized cognitive task-related increases in Oxy-Hb following both physical activity break conditions, with a greater increase after the STEP as previous studies have found moderate intensity to be beneficial on cognitive outcomes [16]. However, we only found a significant increase following the SRA condition and a tendency towards an increase following the STEP. These findings are similar to a study in adults that found that following moderate-intensity physical activity, working memory was improved in parallel with increased brain activation (measured with functional magnetic resonance imaging, fMRI) [41]. However, following the higher-intensity exercise no change in working memory was seen and was in parallel with decreased brain activation41. Considering the inverted U-shape relationship between physical activity intensity and working memory performance it is possible that the less intense SRA condition in the current study was more beneficial for working memory performance, compared to the STEP condition [17], which was of higher intensity (as indicated by the higher heart rate and RPE). A decrease in cognitive task-related changes in Oxy-Hb has also been observed with increased physical activity intensity among adults [15]. To better understand the mechanisms of why the physiological responses differ across physical activity intensities, future studies should collect other blood flow measures, such as arterial spin labeling to measure perfusion [42] or transcranial Doppler to measure blood flow velocity in the medial cerebral arteries [43].

However, it is important to put the changes in Oxy-Hb in parallel with the changes in working memory performance. In a previous study in adults there was a significant decrease in Oxy-Hb following the high-intensity breaks, simultaneously with the improvement in the cognitive task [10]. One suggested reason for this is that when the participants solved the task more efficiently, less resources were needed. Another explanation could be that resources are being redirected to other brain regions. One study found an increase in neural activation (measured with fMRI) in the bilateral parietal cortices, left hippocampus, and the bilateral cerebellum with improvement in working memory performance following a physical activity bout [44]. However, our montage only covered the prefrontal cortex as we were interested specifically in this region, thus we were unable to measure other cortical areas.

The effects of different types of physical activity breaks on cognitive performance have been investigated previously, although seldom in the same sample or in adolescents. In the current study, we found improvements in reaction time following both types of physical activity breaks, with significant improvements following the low intensity simple resistance (SRA) breaks and approaching significance ($p=0.05$) following the higher intensity (STEP) breaks. The inverted U-shaped relationship could be a reason for the more favorable results following the SRA despite being of lower intensity, and why a previous study found improvements only following a bout of resistance training and not following a bout of aerobic exercises [7] or high-intensity interval exercise breaks [45]. However, a similar study of adults found improvement following higher intensity breaks (75–80% of maximal heart rate), whereas no improvements were seen following simple resistance activity breaks [10]. Positive effects on cognitive performance have also been found in children (mean age 8.8 years) following physical activity at 90% of maximal heart rate [20]. As previously mentioned, the intensity threshold of when cognitive performance starts to decline is unknown and could vary between populations [15], which could explain why we see different responses in adults, children and adolescents.

Another potential reason why we did not find more significant improvements in working memory (such as in accuracy) could have been that the power calculations were based on cognitive task-related changes in Oxy-Hb. Therefore, Cohen's d-effect sizes were calculated to assess the magnitude of the changes in working memory performance. We observed the largest effect sizes ($d \geq 0.8$) in reaction time during the easiest task (1-back), with more favorable results in the prolonged sitting (SOCIAL) condition, compared to the physical activity break conditions. In the most difficult task (3-back) the opposite was seen, with more favorable results with moderate effect sizes ($d \geq 0.6$) following the physical activity breaks compared to the SOCIAL condition. These are in line with the changes in Oxy-Hb, where a significant decrease was found following prolonged sitting, but increases after the physical activity breaks. Considering these results, it could be argued that when students perform a task with low cognitive demand (such as the 1-back), it might be beneficial to remain seated. However, with increased cognitive demand, it could be beneficial to break up the sitting with short physical activity breaks.

According to the neural efficiency hypothesis, the pattern of change (assessed by task-related changes in Oxy-Hb in this study) depends on a person's cognitive processing skills. Individuals with good cognitive processing skills require less resources and elicit a smaller physiological response (changes in Oxy-Hb), whereas individuals with less efficient processes elicit a larger response [46]. Therefore, we performed an exploratory analysis to investigate if baseline working memory performance would moderate the effect of the interventions. In the 3-back we found a moderating effect following the STEP condition only, where the group with baseline performance below the median significantly improved their reaction time and accuracy, whereas the above-median group had a significant decrease in accuracy. These results are in line with the findings by Drollette et al., that acute physical activity could be more beneficial for students with lower working memory performance at baseline [47]. In the stratified fNIRS analyses, we found that there was an intervention effect of both physical activity breaks, which was only significant in the below median group. Another interesting finding was that the pattern of change following the STEP condition differed between the groups. In the below median group, a decrease in Oxy-Hb was visible, in parallel with the significant improvements in working memory performance during the 3-back. However, in the group with working memory performance above the median, an increase in Oxy-Hb was visible simultaneously with a significantly worse performance in accuracy.

Although the changes in Oxy-Hb were not significant, these findings suggest that following the STEP condition, the below median group might have utilized less resources, yet was more effective at solving the working memory task. However, these analyses were performed in a subgroup so larger studies are needed before these findings can be generalized to the broader group of adolescents.

Strengths and limitations

A limitation of the current study is the lack of standardization of the student's schoolwork performed during the session. Depending on how cognitively demanding their schoolwork was, this could potentially impact the cognitive and fNIRS measures. However, cognitive engagement varies during a school day, so this also increases the ecological validation of the study. Moreover, while the aim was to compare physical activity breaks to the prolonged sitting condition, it is important to note that the two types of physical activity breaks differed in type (resistance vs. aerobic) and intensity (low vs. high). This makes it difficult to disentangle what aspect of the physical activity break caused the different response we observed between the breaks. Furthermore, there was a discrepancy of intensity classification of the STEP condition; when using percent of estimated heart rate max it would be clarified as high intensity, whereas using the RPE from the Borg scale it would be categorized as moderate intensity, this also limits the conclusions drawn based on intensity level. Further, due to a lack of similar studies in the field, the power calculation for this study was based on studies with slightly different designs, protocols, and older populations, which might explain why we did not see a more profound change in Oxy-Hb. It should also be noted that this study was performed in a small group of healthy adolescents, so the results might not be generalizable to other groups of adolescents. Additionally, due to the necessity of conducting fNIRS measures before potential changes in cerebral blood flow returned to baseline following physical activity breaks, we were unable to employ an optode registration system to verify the positions of the optodes over specific prefrontal cortex regions. Consequently, we had to analyze the prefrontal cortex more broadly, rather than focusing on specific channels, but could also examine the left and right hemispheres (see Supplemental material). In addition, as we only had a prefrontal cortex montage, we could not examine other brain regions associated with working memory (e.g., parietal cortices), which could have offered a more comprehensive understanding of the cognitive effects observed in our study. Some strengths of the current study include using short-separation channels together with the long-channels in order to extract confounders from superficial blood flow, which has not been previously rigorously employed. In addition, a robust study design (randomized cross-over design) was employed, which allows participants to be their own control and increases the internal validity. Further, the physical activity breaks investigated in this study are likely feasible to implement in a school setting as they are short, pre-recorded, and can be performed in a limited space. Lastly, although we assume that cognitive performance and changes in cerebral blood flow are linked, future studies should also investigate other factors such as changes in neurotrophic factors and brain neurotransmitters [48] simultaneously to better understand these physiological mechanisms.

Conclusion

We found a significant intervention effect after implementing short physical activity breaks during a proloned sitting session, suggesting these breaks could prevent the decrease in prefrontal Oxy-Hb which occurs following prolonged sitting. These changes were found in parallel with improvements in the working memory task, indicating that changes in cerebral blood flow could be one physiological mechanism contributing to the improvements. For students with lower working memory performance at baseline, the aerobic moderate-to-vigorous-intensity breaks appeared to be more beneficial for working memory performance. However, for those with high working memory performance at baseline, these breaks had a negative effect on working memory performance. Our findings create a paradigm for future studies to tailor physical activity interventions to improve cognitive performance among adolescents. Future studies should investigate the feasibility, acceptability, and effects of these physical activity breaks in a school setting.

Abbreviations

AR-IRLS	Auto Regressive iteratively reweighted least squares
BMI	Body mass index
deOxy-Hb	Deoxygenated hemoglobin
fMRI	Functional magnetic resonance imaging
deOxy-Hb	Functional near-infrared spectroscopy
fNIRS	Deoxygenated hemoglobin
GLM	General linear model
IQR	interquartile range
ms	Milliseconds
MVPA	Moderate-to-vigorous physical activity
Oxy-Hb	Oxygenated hemoglobin
SRA	Simple resistance activity break condition
SOCIAL	Social activity break condition
STEP	Step-up activity break condition
SD	Standard deviation
β	Unstandardized Beta coefficients

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-024-19306-y.

Supplementary Material 1

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Author contributions

All authors contributed to the conception and design of the study and were involved in the data collection. EH and KK performed the statistical analysis. OT and EH cleaned the fNIRS data. KK drafted the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets are not available for download as the ethical approval does not permit this, however, the disidentified data are available on reasonable request to the first author. The data are held at the Swedish School of Sport and Health Sciences, Sweden.

Declarations

Ethics approval and consent to participate

The study has ethical approval from the Swedish Ethical Review Authority (DNR: 2020–02597) and was conducted in accordance with the Declaration of Helsinki. All students and their parents provided written informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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