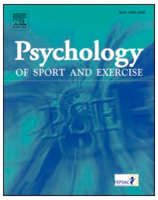
Psychology of Sport & Exercise 66 (2023) 102404

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport



Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge?[☆]

Sofia Anzeneder[a,*], Cäcilia Zehnder[a], Anna Lisa Martin-Niedecken[b], Mirko Schmidt[a], Valentin Benzing[a]

[a] *Institute of Sport Science, University of Bern, Bern, Switzerland*
[b] *Department of Design, Zurich University of the Arts, Zurich, Switzerland*

ARTICLE INFO

Keywords:
Physical activity
Exergaming
Cognitive engagement
Executive function
Attention network task

ABSTRACT

Acute bouts of exercise have the potential to benefit children's cognition. Inconsistent evidence on the role of qualitative exercise task characteristics calls for further investigation of the cognitive challenge level in exercise. Thus, the study aim was to investigate which "dose" of cognitive challenge in acute exercise benefits children's cognition, also exploring the moderating role of individual characteristics. In a within-subject experimental design, 103 children ($M_{age} = 11.1$, $SD = 0.9$, 48% female) participated weekly in one of three 15-min exergames followed by an Attention Network task. Exergame sessions were designed to keep physical intensity constant (65% HR_{max}) and to have different cognitive challenge levels (low, mid, high; adapted to the ongoing individual performance). ANOVAs performed on variables that reflect the individual functioning of attention networks revealed a significant effect of cognitive challenge on executive control efficiency (reaction time performances; $p = .014$, $\eta_p^2 = .08$), with better performances after the high-challenge condition compared to lower ones ($ps < .015$), whereas alerting and orienting were unaffected by cognitive challenge ($ps > .05$). ANOVAs performed on variables that reflect the interactive functioning of attention networks revealed that biological sex moderated cognitive challenge effects. For males only, the cognitive challenge level influenced the interactive functioning of executive control and orienting networks ($p = .004$; $\eta_p^2 = .07$). Results suggest that an individualized and adaptive cognitively high-challenging bout of exercise is more beneficial to children's executive control than less challenging ones. For males, the cognitive challenge in an acute bout seems beneficial to maintain executive control efficiency also when spatial attention resources cannot be validly allocated in advance. Results are interpreted referring to the cognitive stimulation hypothesis and arousal theory.

1. Introduction

A wide evidence base supports the transient effects of acute exercise (i.e., a single bout of exercise[1]) on children and adolescents' executive functions (EFs; Chang et al., 2012; de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Donnelly et al., 2016). EFs are a set of higher-level cognitive processes underlying the organization and control of adaptive and goal-directed behavior (Diamond, 2013). Among core EFs, inhibition includes the ability to suppress or resist automatic responses (response inhibition), suppress thoughts and memories (cognitive inhibition), and exert control over interference (executive interference control; Diamond, 2013). The latter is conceptually placed at the intersection between the broad constructs of EFs and attention. Executive control is one of three independent yet interacting attention networks, along with alerting (achieving and maintaining an alert state) and orienting (selecting information from sensory input; Petersen & Posner, 2012).

Regarding after-effects of acute exercise on executive control in children and adolescents, meta-analytic findings show positive effects, with ES ranging from 0.28 to 0.57 (de Greeff et al., 2018; Ludyga, Gerber, Brand, Holsboer-Trachsler, & Puhse, 2016; Verburgh, Königs, Scherder, & Oosterlaan, 2014). To better understand the underlying

---

[☆] Mirko Schmidt and Valentin Benzing share senior authorship.

[*] Corresponding author. Bremgartenstrasse 145, 3012, Bern, Switzerland.
E-mail address: sofia.anzeneder@unibe.ch (S. Anzeneder).

[1] In 'exercise and cognition' research, the meaning of the term 'exercise' has been expanded to encompass any specific form of physical activity that is planned, structured, and purposive to maintain or improve outcomes in different domains (e.g., physical, cognitive; Herold et al., 2021).

https://doi.org/10.1016/j.psychsport.2023.102404
Received 28 July 2022; Received in revised form 26 November 2022; Accepted 8 February 2023
Available online 10 February 2023
1469-0292/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

mechanisms of these effects, it is important to consider how executive control interacts with other attention networks (alerting and orienting). However, the available evidence of acute exercise effects on alerting and orienting networks is limited, with studies investigating only the individual functioning of these networks in children (van den Berg et al., 2018) and adults (Chang, Pesce, Chiang, Kuo, & Fong, 2015), without considering their interactive functioning with executive control. Although positive results on EFs generally seem consistent, there is considerable heterogeneity in the magnitude of effects (Lubans, Leahy, Mavilidi, & Valkenborghs, 2022). As a result, research increasingly focused on a variety of quantitative and qualitative exercise task characteristics that may moderate effects on EFs.

One of the qualitative characteristics of exercise most widely discussed in recent years as having an impact on children's EFs is cognitive challenge (or demand) inherent in motor tasks (Best, 2010; Pesce, 2012; Tomporowski, McCullick, Pendleton, & Pesce, 2015). Cognitive challenge is thought to induce cognitive engagement, which is defined as the degree to which the allocation of attentional resources and cognitive effort is needed to master complex tasks (Pesce, 2012). The empirical evidence concerning the beneficial effects of cognitive challenge in acute exercise on children's EFs is, however, limited and inconsistent (Paschen, Lehmann, Kehne, & Baumeister, 2019). Compared to less cognitively challenging acute bouts of exercise, some studies revealed positive effects in favor of the more challenging conditions (Benzing, Heinks, Eggenberger, & Schmidt, 2016; Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro, & Tidow, 2008; Flynn & Richert, 2018; Jäger, Schmidt, Conzelmann, & Roebers, 2014; Schmidt, Benzing, & Kamer, 2016), while others found no difference (Bedard, Bremer, Graham, Chirico, & Cairney, 2021; Best, 2012; Jäger, Schmidt, Conzelmann, & Roebers, 2015; van den Berg et al., 2016; Wen, Yang, & Wang, 2021), or even detrimental effects (Egger, Conzelmann, & Schmidt, 2018; Gallotta et al., 2012, 2015). Inconsistent findings may be due to differences in exercise characteristics (e.g., applied durations, intensities, modalities), interacting with individual characteristics (e.g., developmental stage, biological sex, skill level, previous experience; Schmidt, Egger, Anzeneder, & Benzing, 2021). Therefore, systematic investigations of dose-response relations among cognitive challenge levels and children's EFs are needed (Schmidt et al., 2021).

Thus, the rationale behind the present study has both practical and theoretical relevance. From a practical point of view, cognitively challenging bouts of exercise are inherently varying and therefore more suitable for children's preferences than bouts with low cognitive demands (Paschen et al., 2019). Most importantly, from a theoretical point of view, the assumptions of the cognitive stimulation hypothesis on the effect of cognitive engagement on EFs can be investigated. According to this hypothesis, a cognitively challenging and physically active task performance activates similar frontal-dependent circuitries as sedentary EFs tasks (Best, 2010; Tomporowski et al., 2015), resulting in more efficient executive functioning that continues after the cessation of the activity (Budde et al., 2008; Pesce, 2012). The activation is expected to be strongest when the task is novel, requires concentration, and the response is unpredictable and fast (Best, 2010). However, only studies in which the cognitive challenge level is systematically manipulated and individually adapted to match children's skill level, while exercise modality and physical exercise intensity are held constant, can provide insights on the assumptions of the cognitive stimulation hypothesis.

One tool that allows for the controlled manipulation and individualization of both physical and cognitive challenges of exercise is exergaming. Exergaming (or active video gaming) is a portmanteau of "exercising" and "gaming" (Benzing & Schmidt, 2018). It has been shown that exergaming can be a motivating, physically and cognitively challenging form of acute exercise for children and adolescents (Benzing et al., 2016; Best, 2012; Ketelhut, Röglin, Martin-Niedecken, Nigg, & Ketelhut, 2022). To date, only a few studies have investigated the effect of cognitive challenge in acute exergaming on children's and adolescents' EFs (Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018). While in two studies, cognitively challenging exergaming was found to be superior to a less challenging exergaming (Benzing et al., 2016) or aerobic exercise (Flynn & Richert, 2018), another study found physical exercise intensity and not the level of cognitive challenge to be the performance determinant (Best, 2012). Diverging acute study results on the effect of cognitive challenge within exergaming depict the need to consider specific aspects in acute cognitively challenging exercise studies. (1) First, while well-designed exergaming studies controlled for physical exercise intensity, perceived exertion, and other potential confounders (e.g., pleasure), they used completely different exercise types (Best, 2012; Flynn & Richert, 2018) or different exergames to manipulate cognitive challenge (Benzing et al., 2016). Thus, it is likely that the experimental conditions did not only differ in cognitive challenge but also in physical task demands, not allowing to disentangle the individual and combined effects of cognitive and physical challenges on EFs. (2) Second, previous studies did not adapt the dosage of cognitive challenge within the acute exercise to the individual skill level. Analogously to what has been proposed for the individualization of quantitative characteristics (i.e., intensity, duration; Herold, Müller, Gronwald, & Müller, 2019, 2021), it seems beneficial to individualize also the cognitive demands of the exercise task to the respective skill level.

Thus, the aim of the current study was threefold. (1) The primary aim was to investigate which "dose" of cognitive challenge in an acute exergaming-based exercise benefits children's executive control the most. (2) The second aim was to extend the focus from the most commonly studied executive control to incorporate other attention networks (alerting and orienting, including their interactive functioning). (3) The third aim was to explore whether individual characteristics (e.g., age, sex, need for cognition, fitness) interact with task constraints (cognitive challenge levels) to determine an optimal challenge point.

Our hypotheses were: (1) A higher cognitive challenge should elicit larger executive control gains, in line with the cognitive stimulation hypothesis. (2) Considering that acute exercise studies addressing aftereffects on alerting and orienting are limited and inconsistent (Chang, Pesce, et al., 2015; van den Berg et al., 2018) and none investigated the interaction among attention networks, no a priori hypothesis was stated. Since, however, attention network literature shows that executive control efficiency is worse when attention cannot be alerted or spatially oriented in advance (Fan et al., 2009), we explored if the level of cognitive challenge in acute exercise influenced the interactive functioning of executive control with other attention networks. (3) Given the limited evidence on the moderating role of individual characteristics regarding the effects of acute cognitively challenging exercise, no a priori hypothesis was formulated.

2. Methods

This trial is part of the project "School-based physical activity and children's cognitive functioning: The quest for theory-driven intervention". The project aims to investigate the effects of qualitative and quantitative characteristics of designed school-based physical activity on children's cognitive functions. The project was registered in the German Clinical Trials Registry (registration number: DRKS00023254). The cantonal ethics committee approved the study protocol (number: 2020-00624), which adhered to the latest declaration of Helsinki.

2.1. Participants

A total of 103 children, aged 10–13 years ($M = 11.1$, $SD = 0.9$; 48% female), were recruited from five primary schools in the canton of Bern (Switzerland). The legal guardians of all children provided informed written consent and children agreed to participate. The exclusion criteria were any neurological, developmental, or medical condition that would affect the subjects' integrity or study results. To determine sample size, we conducted a simulated power analysis using the SuperPower Shiny app (https://shiny.ieis.tue.nl/anova_power/). We defined a within-subjects design with three cognitive challenge conditions and estimated effects based on previous exergaming evidence (Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018) with alpha error probability = .05 and correlation between the repeated measures $r = 0.61$. We assumed that children's executive control performance would be faster after the high-challenging condition ($M = 135$, $SD = 80$), compared to the mid ($M = 155$, $SD = 80$) and low one ($M = 175$, $SD = 80$). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed that a power of 99% for repeated measures ANOVAs and more interestingly a power of 80% for *t*-test comparisons among cognitive challenge conditions would be favorable to detect effects.

We continuously recruited participants. Of the 110 participants recruited, two were injured during the study period and five were identified as multivariate outliers based on the Mahalanobis distance ($p < .001$), and were therefore excluded. Due to technical problems with the tablets used for ANT assessments (SurfTab 10.1, TrekStor GmgH, Lorsch, Germany), there was some loss of data (4.7%). Since the MCAR test has led to a non-significant result ($p = .662$), the missing values were imputed using the expectation-maximization algorithm. Participants' background variables are presented in Table 1.

2.2. Design and procedures

In the current within-subject crossover design study with counterbalanced order of experimental conditions (six possible permutations), the cognitive challenge of an acute bout of exergaming was manipulated to be low, mid, or high (whereby each level was individually adapted according to the ongoing individual performance).

The study was conducted over four weeks. During the first study week, data were collected in two visits. On the first visit, children filled out a questionnaire about their background characteristics [age, biological sex, height, weight, socioeconomic status (Torsheim et al., 2016), pubertal developmental status (Watzlawik, 2009), habitual physical activity (Kowalski, Crocker, & Faulkner, 1997), need for cognition (Preckel, 2014), need for affect (Appel, Gnambs, & Maio, 2012), and previous videogame expertise]. Subsequently, they performed a 20-m Shuttle Run test (Léger, Mercier, Gadoury, & Lambert, 1988) to assess their maximum heart rate (HR) and fitness level. Acceptable reliability and validity were demonstrated for background variables; only the videogame expertise questionnaire was self-developed for the current study (for a detailed description of background variables see Appendix A). In the second visit, children participated in a procedure familiarization session. Each child completed a specifically developed tutorial for exergaming tasks, in which each movement was explained and the exergame continued only when movements were carried out correctly, followed by a 3-min regular version of the exergame. The attentional testing was familiarized using the practice block of the Inquisit 5 Millisecond Software (for details, see 'Cognitive measures'). Between the second and the fourth week, children played one exergaming session per week, blinded to the level of cognitive challenge. Before (T_0), during (T_1 and T_2), and after (T_3) exergaming, manipulation check and control variables, including perceived physical exertion, cognitive engagement, pleasure, arousal and stress were collected (see 'Manipulation check' and 'Control variables' sections). During the exergaming task, children wore HR-monitoring devices. In total, each visit lasted about 35 min, including a short assessment break before exergaming (T_0), 2 min warm-up, 15 min of exergaming intermitted by one short assessment break every 5 min of activity (T_1, T_2, T_3), a water break after the exergaming, and the subsequent cognitive functioning assessment with ANT-R (Fan et al., 2009). The experimental protocol of the individual weekly sessions can be seen in Figure 1. Children were tested one after another so that when the first child started the attentional testing, the second one started the exergaming. Per day, a maximum of 10 children were tested. Testing and evaluation were conducted by the first author together with a team of trained research assistants and sport science students.

Table 1
Participants' background variables.

Background variables	*M* (*SD*)
Age (years)	11.1 (0.9)
Biological sex (% female)	48%
Socioeconomic status [2–14]	8.4 (1.3)
Body mass index (kg/m^2)	18.1 (3.1)
Pubertal developmental status [3–12]	4.7 (2.0)
Habitual physical activity [1–5]	2.6 (0.6)
VO$_2$max (ml/kg/min)	50.9 (5.2)
Videogame expertise [1–7]	3.8 (2.5)
Need for cognition [19–95]	57.7 (12.5)
Need for affect [-30–30]	6.7 (7.4)

2.3. Intervention and experimental conditions

Exergaming sessions took place in the school during school hours and were performed individually, once weekly, at the same time and day each week. The intervention consisted of a modified, screen-based version of the exergame Sphery Racer, played within a 3 × 2 m playing field (Martin-Niedecken, Rogers, Turmo Vidal, Mekler, & Márquez Segura, 2019, 2020). During the exergame session, participants wore four motion-based trackers (HTC Vive tracking sensors, Vive, Seattle, United States) attached to their wrists and ankles as well as an HR sensor (Polar Team2 straps and transmitters; Polar Electro Oy, Kempele, Finland) to constantly track their movements and body position, and their HR, respectively. The physical intensity was held constant during the session at 65% HR$_{max}$. Participants were projected directly into the virtual reality on a screen by integrated cameras and were taken by the game on a rapid sci-fi-themed underwater race. They navigated an avatar and passed various colored gates. Each gate requested a specific functional workout movement and/or cognitive task. Jumps, squats, skipping, and deep lunges were used to maintain the HR constant (50% of total movements). Punches and catching sideway points were used to manipulate the cognitive challenge (50% of total movements). Exergaming tasks were designed to mirror attentional allocation processes involved in the ANT paradigm. The tasks included anticipatory cues that alerted and oriented attention, and targets to be responded to with movement actions while ignoring distracting stimuli (for exergaming tasks see description and video in Appendix B and D). The level of cognitive challenge for each condition was predefined by an ascending number of distracting stimuli (low: 5–15%, mid: 20–35%, high: 40–60%) and misleading cues (low: 1–5%, mid: 7–12%, high: 13–19%) which preceded punches and catching sideway points movements. Within each condition, the level of cognitive challenge was constantly adapted to the ongoing individual performance (within the ranges mentioned above of distracting stimuli and misleading cues). The exergaming task was rendered easier or more difficult if the participant made more or less than three errors in 8 min, 1 min, or 30 s in the low-, mid-, and high-challenge conditions, respectively.

Supplementary video related to this article can be found at http://doi.org/10.1016/j.psychsport.2023.102404

2.4. Manipulation check

Several variables were assessed to test whether experimental manipulation had succeeded (see Figure 1). PolarTeam2 belts and transmitters (Polar Electro Oy, Kempele, Finland) were used to measure children's HR during exergaming (measurement every 3 s) and to adjust the physical intensity at 65% HR$_{max}$. In addition, the *perceived physical exertion* (RPE) was measured using the Borg RPE scale for perceived physical exertion (Borg, 1982). Evidence for acceptable reliability and

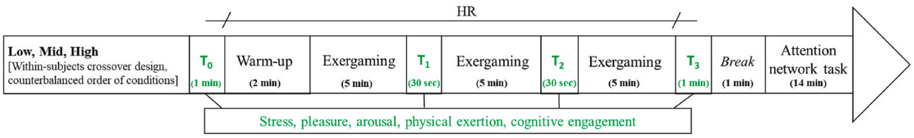


Figure 1. Experimental protocol of the weekly sessions.
Note. T_0 = before exergaming (pre); T_1 = 5 min exergaming; T_2 = 10 min exergaming; T_3 = after exergaming (post).

validity of the Borg RPE scale in preadolescents has been provided (Lamb, 1996). To determine children's *cognitive engagement* during exergaming, the Borg RPE scale was adapted to ask for the perceived cognitive engagement (RCE) of the activity. The question they had to answer was "How exhausting was the previous activity for your brain?". This adapted version is not a validated instrument but proved to be feasible with children and adolescents and sensitive to detect changes in cognitive engagement among intervention conditions (Benzing et al., 2016; Egger et al., 2018; Schmidt et al., 2016).

2.5. Control variables

Pleasure, arousal, and perceived stress were assessed using the single-item pictorial Self-Assessment-Manikin scale (see Figure 1). Evidence for an acceptable reliability and validity of the scale has been proven (Bradley & Lang, 1994).

2.6. Cognitive measures

A child-adapted version of the Attention Network Task (ANT-R; Fan et al., 2009) was used on Inquisit 5 (Millisecond Software, Seattle, WA) to assess the efficiency of: (a) the *executive control* (primary outcome), (b) *alerting* and *orienting networks*, as well as (c) *the interactive functioning of executive control with alerting and orienting networks*. For the primary outcome, retest reliability ranging from 0.61 to 0.71 has been shown (Macleod et al., 2010).

To capture the functioning of attention network systems, the test combines the Attention cueing paradigm (Petersen & Posner, 2012), that assesses alerting and orienting, and the Flanker task (Eriksen & Eriksen, 1974), that assesses executive control. There are four cue conditions: no cue, double cue, valid spatial cue, and invalid spatial cue; and two congruency conditions: a central target arrow surrounded by congruent (>> > > > or < < < < <) or incongruent (>> < > > or < < > < <) lateral flanker arrows. Each trial begins with a central fixation cross, followed by no cue, a double cue informing that a target will occur soon, or a single spatial cue informing on the probable location of the upcoming target. A valid spatial cue indicates the location where a subsequent target will appear. An invalid spatial cue indicates the opposite location. Subsequently, a congruent or incongruent flanker condition appears. Children's task is to identify the direction of the center arrow by pressing a right or left button while ignoring the lateral flanker arrows. Reaction times (RTs) and response accuracy are recorded. The task comprises two blocks of 72 trials (each bock with 12 no cue, 12 double cue, 36 valid spatial, and 12 invalid spatial trials) and lasts 14 min, including a 1-min break between the blocks. Responses with RTs faster than 200 ms or longer than 1700 ms were excluded automatically by the program (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Further details on the task parameters and cue-target interval timing can be found elsewhere (Fan et al., 2009). Each attention system performance is computed as a difference value of RTs and accuracy.

- *Executive control* (flanker effect) is calculated as [incongruent – congruent trials]. A smaller value for the RT difference and a smaller negative value for the accuracy difference reflect a better efficiency, because children can better inhibit the interference of incongruent flankers.
- *Alerting* is calculated as [no cue – double cue trials]. A larger value for the RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by an alerting cue.
- *Orienting* involves engaging attention at a validly cued location [double cue – valid spatial cue trials] and disengaging attention from an invalidly cued location [invalid spatial cue – double cue trials]. A larger RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by a valid spatial cue, and/or the cost elicited by an invalid spatial cue.

The interactive function of the three attention networks is assessed as the effect of alerting or orienting on executive control (flanker effect). It is measured as the difference of flanker effect under different cue conditions.

- The *effect of alerting on executive control* is calculated as [(no cue trials with incongruent flanker – no cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. A negative value indicates a negative impact of alerting on executive control.
- The *effect of orienting on executive control* is composed of the effects of *engaging* and *disengaging* attention on executive control. The effect of *engaging* is calculated as [(double cue trials with incongruent flanker – double cue trials with congruent flanker) – (spatial valid cue trials with incongruent flanker – spatial valid cue trials with congruent flanker)]. The effect of *disengaging* is calculated as [(spatial invalid cue trials with incongruent flanker – spatial invalid cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. For *engaging*, a positive value indicates the beneficial effect of validly oriented attention on executive control. Instead, for *disengaging*, a positive value indicates the cost of invalidly oriented attention.

2.7. Statistical analyses

All analyses were performed using SPSS version 27.0 (SPSS Inc., Chicago, IL, USA). Preliminary analyses were run using repeated measures ANOVAs for the comparison of manipulation check (RPE, RCE) and control variables (pleasure, arousal, stress) among cognitive challenge conditions (low, mid, high) over exergaming time [pre (T_0), during (mean of T_1, T_2), and post (T_3)]. Post-hoc Bonferroni adjusted pairwise comparisons were reported for the cognitive challenge effect of interest. A further ANOVA was run to compare HR average among cognitive challenge conditions (low, mid, high).

To analyze the effect of the cognitive challenge level on attention network performances, a 3 (cognitive challenge level) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVA was performed separately for RTs and response accuracy. In the case of significant interactions, RT and accuracy differences were computed by subtracting cue and flanker conditions pairwise in a theory-driven manner (see 'Cognitive measures' section) to limit the amount of post-hoc comparisons and inflated risk of type II error. Thus, these difference values were used to contrast the cognitive challenge levels of interest using post-hoc Bonferroni adjusted pairwise comparisons.

To explore the role of individual characteristics on the cognitive challenge effects on attention networks, continuous individual background variables were first entered as covariates in a 3 (cognitive challenge level) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANCOVA. In the case of significant interactions of a covariate with the cognitive challenge factor, that variable was dichotomized and included as a categorical moderator in a subsequent ANOVA. The dichotomous sex variable was directly entered in the subsequent ANOVA as a moderator. In the case of significant interactions, including potential moderators, performances after the three cognitive challenge conditions were contrasted using the above-mentioned RT and accuracy difference values separately for the levels of the moderator variable.

For all analyses, median RTs were used because of the disproportional contribution of outliers in mean RTs for different participants and due to the non-normal distribution of RTs. All analyses were also performed on mean RTs, with and without the five multivariate outliers. Results depict median RTs with multivariate outliers excluded. The significance level was set at $p < .05$ for all analyses, and η_p^2 was reported as an effect size estimation.

3. Results

3.1. Manipulation check

Descriptive statistics of manipulation check variables among time points (pre, during, post) and cognitive challenge conditions (low, mid, high) are presented in Appendix C. The ANOVA revealed a significant effect of time (pre, during, post), cognitive challenge (low, mid, high), and their interaction on RPE [Time: $F(2, 101) = 152.63$, $p < .001$, $\eta_p^2 = .75$; Cognitive challenge: $F(2, 101) = 4.02$, $p < .021$, $\eta_p^2 = .07$; Cognitive challenge × Time: $F(4, 99) = 2.48$, $p = .049$, $\eta_p^2 = .09$] and RCE [Time: $F(2, 101) = 94.48$, $p < .001$, $\eta_p^2 = .65$; Cognitive challenge: $F(2, 101) = 10.21$, $p < .001$, $\eta_p^2 = .17$; Cognitive challenge × Time: $F(4, 99) = 2.37$, $p = .058$, $\eta_p^2 = .09$]. As concerns the cognitive challenge effect of interest, Bonferroni adjusted pairwise comparisons showed that the high-challenge condition was perceived as the most physically effortful (high vs. mid: $p = .048$, $\eta_p^2 = .03$; high vs. low: $p = .091$, $\eta_p^2 = .02$) and cognitively engaging (high vs. low: $p < .001$, $\eta_p^2 = .07$; high vs. mid: $p = .045$, $\eta_p^2 = .03$), whereas the low- and mid-challenge conditions were perceived as equally demanding ($ps > .256$, $\eta_{ps}^2 < .02$; see Appendix C). However, the difference in RPE among conditions was not paralleled by objective HR data ($p = .319$; $\eta_p^2 = .02$), which instead confirmed the intended similarity of physical challenge across conditions.

3.2. Control variables

Descriptive statistics of control variables among time points (pre, during, post) and cognitive challenge conditions (low, mid, high) are presented in Appendix C. The ANOVA revealed a significant effect of time (pre, during, post), cognitive challenge (low, mid, high), and their interaction on pleasure [Time: $F(2, 101) = 10.52$, $p < .001$, $\eta_p^2 = .17$; Cognitive challenge: $F(2, 101) = 8.77$, $p < .001$, $\eta_p^2 = .15$; Cognitive challenge × Time: $F(4,99) = 5.47$, $p = .001$, $\eta_p^2 = .18$], arousal [Time: $F(2, 101) = 20.99$, $p < .001$, $\eta_p^2 = .29$; Cognitive challenge: $F(2, 101) = 3.37$, $p = .038$, $\eta_p^2 = .06$; Cognitive challenge × Time: $F(4,99) = 3.08$, $p = .019$, $\eta_p^2 = .11$], and stress [Time: $F(2, 101) = 31.19$, $p < .001$, $\eta_p^2 = .38$; Cognitive challenge: $F(2, 101) = 4.76$, $p = .011$, $\eta_p^2 = .09$; Cognitive challenge × Time: $F(4,99) = 1.16$, $p = .34$, $\eta_p^2 = .05$]. As concerns the cognitive challenge effect of interest, Bonferroni adjusted pairwise comparisons showed that the high-challenge condition was perceived as the least pleasant (high vs. low: $p < .001$, $\eta_p^2 = .04$; high vs. mid: $p = .006$, $\eta_p^2 = .02$) and arousing (high vs. mid: $p = .031$, $\eta_p^2 = .02$; high vs. low: $p = .780$, $\eta_p^2 = .03$), and most stressful (high vs. low: $p = .009$, $\eta_p^2 = .02$; high vs. mid: $p = .200$; $\eta_p^2 = .02$), even though with limited (small to medium) effect sizes (see Appendix C).

3.3. Cognitive measures

3.3.1. Cognitive challenge effects on executive control, alerting, orienting, and their interaction

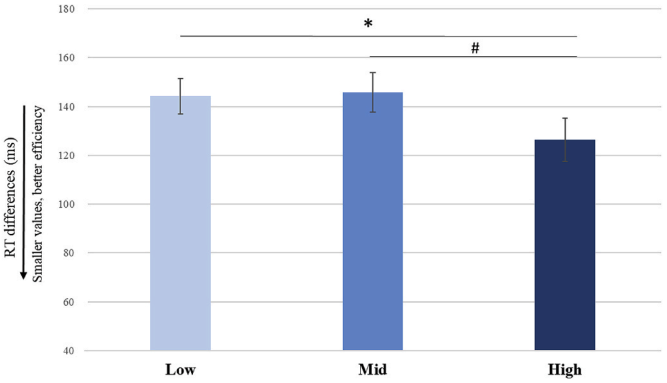
The first ANOVA on RTs revealed the classic Cue- [$F(3, 100) = 355.11$, $p < .001$, $\eta_p^2 = .91$], Flanker- [$F(1, 102) = 372.13$, $p < .001$, $\eta_p^2 = .79$] and Cue × Flanker effects [$F(3, 100) = 41.98$, $p < .001$, $\eta_p^2 = .56$]. These effects are well known in the literature (Fan et al., 2009).

Regarding the primary study aim, a significant Cognitive challenge × Flanker interaction with a medium effect emerged [$F(2, 100) = 4.46$, $p = .014$, $\eta_p^2 = .08$]. This interaction effect shows that the level of cognitive challenge influenced the subsequent efficiency of the executive control network (Figure 2). Post-hoc Bonferroni adjusted pairwise comparisons revealed faster RTs after the high-challenge condition, compared to the low ($p = .045$, $\eta_p^2 = .01$) and mid ones ($p = .011$, $\eta_p^2 = .02$), which in turn did not differ ($p = 1.00$, $\eta_p^2 = .00$). There were no cognitive challenge effects for accuracy ($p = .754$, $\eta_p^2 = .01$).

Concerning the second study aim, no effects of cognitive challenge emerged, in the whole sample, for alerting, orienting, or their interaction with executive control ($ps > .05$, $\eta_{ps}^2 < .01$ for both RTs and accuracy data).

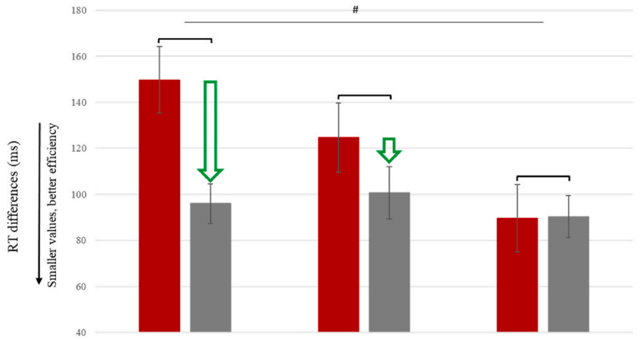
3.3.2. Moderating role of individual characteristics

Concerning the third study aim, ANCOVAs revealed no significant interaction effects of cognitive challenge with age, socio-economic, weight and pubertal status, habitual physical activity level, VO_2max, videogame expertise, need for cognition or need for affect ($ps > .05$, $\eta_{ps}^2 < .03$). A subsequent repeated measures ANOVA on RTs with biological sex as a potential moderator showed a Cognitive challenge × Flanker × Sex interaction with a small to medium effect [$F(2, 100) = 2.50$, $p = .087$, $\eta_p^2 = .05$], as well as a significant Cognitive challenge × Flanker × Cue × Sex interaction with a medium to high effect [$F(6, 96) = 2.33$, $p = .038$, $\eta_p^2 = .13$]. Subsequent ANOVAs were run on RT differences that reflect the flanker effect under different cue conditions (see 'Cognitive measure' section), separately for males and females. Significant differences for cognitive challenge were found only in males and only for the RT differences reflecting the interactive functioning of executive control (flanker effect) with orienting (spatial attention engagement) ($p = .001$, $\eta_p^2 = .22$). Post-hoc Bonferroni adjusted pairwise comparisons revealed a significant difference between the high- and low-challenge conditions ($p = .001$, $\eta_p^2 = .07$). No further comparisons were significant ($ps > .05$, $\eta_{ps}^2 < .03$). To interpret this result, the difference in flanker effect was computed as a function of the preceding cue condition. As indicated by the green arrows in Figure 3, with increasing cognitive challenge level,



	Low	Mid	High
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Flanker effect	144.20 (7.17)	145.83 (8.08)	126.35 (8.88)

Figure 2. Cognitive challenge effects on executive control (flanker effect). *Note.* Flanker effect is computed as RT difference [incongruent – congruent trials]. Error bars represent the standard error of the mean. Significant differences: $^{\#}$high vs. low: $p = .045$, $\eta_p^2 = .01$; *high vs. mid: $p = .011$, $\eta_p^2 = .02$.



	Low	Mid	High
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
🟥 **Double cue**	149.75 (14.38)	124.68 (15.08)	89.56 (14.66)
■ **Spatial valid cue**	95.94 (8.66)	100.62 (11.41)	90.33 (9.02)

Figure 3. Cognitive challenge effects on the interactive functioning of executive control (flanker effect) and orienting (spatial attention engagement) in males.
Note. Red bars = flanker effect under double cue conditions, computed as [Double cue, flanker incongruent – Double cue, flanker congruent]. Grey bars = flanker effect under valid spatial cue conditions, computed as [Valid cue, flanker incongruent – Valid, flanker congruent]. The interactive functioning of executive control and orienting, represented by differences between red and grey bars, is computed as [(Double cue, flanker incongruent – Double cue, flanker congruent) – (Spatial valid cue, flanker incongruent – Spatial valid cue, flanker congruent)]. Error bars represent the standard error of the mean. Significant difference: $^{\#}$high vs. low: $p = .001$, $\eta_p^2 = .07$.

differences in flanker effect between double (red bars) and spatial valid cue conditions (grey bars) decreased. The same analyses performed on accuracy data were not significant ($ps > .05$, $\eta_p^2 < .04$).

4. Discussion

The primary aim of the present study was to investigate the dose-response relation between different levels of cognitive challenge in acute exercise and children's executive control performance using exergaming. The second aim was to test the executive control performance within the frame of the threefold attention network paradigm (Petersen & Posner, 2012) to get more insights into the efficiency of executive control along and interacting with alerting and orienting attention networks. Finally, it was also explored if the optimal dose of cognitive challenge varies according to individual characteristics. In sum, the cognitively high-challenging bout benefited children's executive control the most, whereas the efficiency of alerting and orienting networks was unaffected by the cognitive challenge level. In males only, the benefit for executive control seemed to be due to a transiently increased ability to maintain executive control efficiency also when spatial attentional resources could not be allocated in advance to support conflict resolution.

The present study is the first to directly compare, in children, the acute effects of the (individually adapted) cognitive challenge level in acute exercise on executive control, alerting, and orienting performances and interactions. Consistent with our first hypothesis, results showed that the cognitively high-challenging condition benefited children's executive control the most. In detail, children became faster in conflict resolution while maintaining a high response accuracy. This suggests a benefit for RTs without a speed-accuracy trade-off effect. According to the cognitive stimulation hypothesis,bouts of exercise performed in variable and challenging environments may activate EFs, facilitating the performance in subsequent EF tasks (Best, 2010). Combining cognitive and physical demands may produce synergistic effects due to co-activation and inter-connectedness of the neural areas associated with cognition and movement (referring broadly to the prefrontal cortex and the cerebellum, respectively; Koziol et al., 2014). A further, not mutually exclusive explanation refers to the arousal theory, as both physical exertion and cognitive engagement are arousing and thus enhance attentional resources (Lambourne & Tomporowski, 2010). An inverted U-shaped function between exercise task characteristics and cognitive functioning has been hypothesized and tested, in acute exercise research, only for exercise duration (Chang, Chu, et al., 2015) and intensity (Moreau & Chou, 2019). Regarding cognitive challenge, the current study did not confirm an inverted U-shaped function but an optimal stimulation at the highest cognitive challenge level with no performance differences at lower levels. In sum, these findings support our first hypothesis and are consistent with further studies suggesting that bouts of exercise that elicit high cognitive engagement are beneficial for children's EFs (Benzing et al., 2016; Budde et al., 2008; Flynn & Richert, 2018; Jäger et al., 2014; Schmidt et al., 2016). However, differences in quantitative and qualitative exercise task characteristics, and sample characteristics hinder a thorough comparison with previous studies. The current study used a acute 15 min bout at moderate to vigorous intensity. In previous acute cognitively challenging exercise studies with children and adolescents, durations and intensities varied largely, ranging from 10 to 50 min and from 40 to 75% HR_{max} (Schmidt et al., 2021). Detrimental effects were found only for moderate to vigorousbouts of longest durations (50 min; Gallotta et al., 2012, 2015), or of intermediate durations (20 min) but with younger children (Egger et al., 2018). As regards qualitative exercise task characteristics, most studies investigated the effect of the cognitive challenge level by comparing different exercise modalities (e.g., Bedard et al., 2021; Egger et al., 2018; van den Berg et al., 2016; Wen et al., 2021). To date, only one study manipulated the cognitive demands within the same exercise modality (exergaming; Benzing et al., 2016). The authors showed that the high-challenging condition benefitted adolescents' EFs the most, however, the cognitive demands of the acute exercise were not adjusted individually. Our study overcame this limitation by individualizing the cognitive demands (external load) through adaptation to the ongoing individual performance to limit interindividual variability in cognitive responsiveness (internal load). Thus, while corroborating Benzing et al.'s (2016) findings, the present results can be more univocally attributed to the cognitive challenge level.

Despite of the fine-graded manipulation of the exergaming task demands to generate three cognitive challenge levels (exponentially ascending number of distracting stimuli and misleading cues), the objective increase in cognitive challenge was not reflected in the subjective ratings. Children were able to discriminate only the high-challenging condition from the others, which were perceived as similarly demanding, likely because of the exponential and not linear increase in cognitive challenge across conditions. A further mismatch between objective and subjective data emerged from HR data and physical exertion ratings. Children perceived the cognitively high-challenging condition as physically more demanding, compared to the mid one, although the physical challenge (intensity, duration) was held constant, as also reflected in similar HR across conditions. Taken together, the question arises if children can clearly distinguish physical exertion and cognitive engagement inherent in acute exercise.

Regarding the second aim of the study, results showed that the cognitive challenge level in acute exercise did not influence children's alerting, orienting, or their interaction with executive control. To our knowledge, no previous studies in 'exercise and cognition' research considered the interaction between attention networks. Concerning alerting and orienting, our findings are in line with the available evidence that neither an acute demanding and varied spinning task (Chang, Pesce, et al., 2015), nor routine aerobic exercise (van den Berg et al., 2018) seems to have an effect on alerting and orienting networks. Speculatively, the fact that only executive control but no other attention networks were susceptible to acute exercise might be interpreted according to evidence showing selectively larger effects in performance for tasks that require greater inhibitory control (e.g., flanker task performance for incongruent trials; Lubans et al., 2022).

The third aim of the study was to explore the moderating role of individual characteristics. We found a sex difference in the way the acute high-challenging exercise influenced the interactive functioning of executive control (flanker effect) and orienting (spatial attention engagement). The usual effect reported in general ANT research is worse executive control when spatial attention resources cannot be validly allocated in advance (Fan et al., 2009). In our male subsample, the disadvantage in executive control, when not supported by spatial attentional allocation, was found after the low-challenging exercise condition but progressively decreased and disappeared after the high-challenging bout. These sex differences are consistent with an adult study without physical exercise (Li et al., 2021), showing that the interactive functioning of executive control and orienting networks was more efficient in males, who were less influenced by the validity of the cue. These sex differences were explained as differences in the functional interplay between separate brain areas supporting different aspects of attention. In the present study, males may have exploited the cognitive engagement generated by an acute cognitively high-challenging exercise to compensate the absence of information from external cues to maintain executive control efficiency.

Apart from sex differences, the current study found no further moderating effects of individual characteristics such as age, socioeconomic, weight, pubertal status, fitness level, or need for cognition on attention network performances. It is important to consider that the qualitative and quantitative exercise task characteristics may act, individually or jointly with personal characteristics, as moderators of the acute exercise-cognition relation (Lubans et al., 2022; Pesce, 2009). The fact that no further differential effects have been found could be due to the reciprocal buffering effects of individual and task characteristics (where the latter was individualized in the current study). In the literature, there is diverging evidence on the moderating role of weight status, fitness, and academic achievement. Hwang, Hillman, Lee, Fernandez, and Lu (2021) found that obese children benefited more from cognitively challenging exergaming than their normal-weight counterparts and suggested that this may depend on their lower EFs at baseline. In contrast, Jäger et al. (2015) found that children with higher aerobic fitness and academic achievement benefited most than co-aged lower fit and lower school performers. On the one hand, children with poor baseline performance might benefit most because there is more room for improvement (Diamond & Ling, 2016; Otero, Barker, & Naglieri, 2014). Conversely, cognitively challenging bouts of exercise might benefit only children who are physically and cognitively better equipped to capitalize on it (Herold, Hamacher, Schega, & Müller, 2018, 2021).

4.1. Limitations

This study is not without limitations. First, the comparison of three cognitive challenge levels in acute exercise with counterbalanced order of experimental conditions, but without a sedentary control group, allowed identifying the optimal level of cognitive challenge in exercise but hindered disentangling physical exercise and cognitive engagement related effects. Future studies should include a sedentary control group and utilize a within-subjects crossover design. In this design, all participants engage in both the exercise and sedentary control conditions in a counterbalanced order, and individual differences and learning/practice effects can be controlled (Pontifex et al., 2019).

Second, exercise demands were specifically designed to mirror the ANT paradigm and, thus, might have primed attention effects (Moriarty et al., 2019). The available neural evidence indicates that several distinct neural mechanisms are involved in priming of attention and that priming occurs at multiple stages of perceptual processing (Brinkhuis, Kristjànsson, Harvey, & Brascamp, 2020; Kristjànsson & Àsgeirsson, 2019). These underlying mechanisms resemble those of the cognitive stimulation hypothesis, according to which the exergaming demands of the current study were specifically designed. However, differences between the computerized, sitting ANT task and the whole-body engagement in the exergame which requires gross-motor control (Koziol et al., 2014), as well as typically shorter priming duration effects (Kruijne & Meeter, 2015) render an interpretation in terms of overall priming effect less likely. It remains unclear if, besides near transfer effects of the motor and cognitive demands of the exergaming on ANT performances, far transfer effects on other EFs can also be elicited (Taatgen, 2013). Future studies should evaluate positive and negative attentional priming effects on a variety of more and less distant cognitive measures.

Third, the cognitive challenge level of the exergaming was exponentially increased from the low-to the high-challenging condition. Considering that the cognitive challenge level was individualized and continuously adapted to the performance within the predetermined difficulty levels, an exponential increase was chosen to ensure that children train around their maximum difficulty level in the high condition. To investigate differences between the low and mid conditions in further detail, future studies should explore the impact of a linear incremental trend on children's perceived cognitive engagement and EFs. Additionally, future research might (a) investigate children's ability to perceive different challenge types and the threshold needed to discriminate them, (b) validate existing subjective cognitive engagement measures, and (c) further investigate objective assessments of cognitive challenge such as brain activity or HR variability.

4.2. Conclusions

The current study extends existing evidence by manipulating the cognitive challenge level in acute bouts of exercise in an individualized manner, adapting the cognitive demands to the ongoing individual performance. An acute, cognitively high-challenging exercise transiently enhanced children's executive control but not alerting and orienting performances and interactions. For males only, this enhancement was interpretable as a more efficient executive control, also when spatial attention resources could not be validly allocated in advance. Thus, results underline the relevance of the cognitive challenge "dose" in acute exercise to increase EFs benefits in children. Further studies should investigate the dose-response relation of different durations of acute cognitively challenging exercise in depth, while controlling for the moderating role of individual characteristics. Results of this line of research may be used to implement active breaks and/or physically active learning interventions in the school setting.

Funding

This study was funded by the Swiss National Science Foundation (grant number: 181074).

Author contributions

Conception or design of the work: MS, SA, VB, AN; acquisition of data: SA; data analysis: SA, VB, CZ; interpretation of data for the work: MS, VB, SA; draft of the work: SA, VB. All co-authors revised the work critically for important intellectual content and approved the final version of the manuscript. Furthermore, all co-authors are accountable for all aspects of the work ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethical approval

This study was conducted in the canton of Bern, Switzerland, between February 2020 and June 2022. Ethical approval was granted by the respective cantonal ethics committees (BASEC 2020-00624) and the trial was registered at ClinicalTrials.gov (DRKS00023254).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank the participating teachers, parents and children, as well as the students who helped collecting data, and Amie Wallman-Jones for language editing.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2023.102404.

References

Appel, M., Gnambs, T., & Maio, G. R. (2012). A short measure of the need for affect. *Journal of Personality Assessment, 94*(4), 418–426. https://doi.org/10.1080/00223891.2012.666921

Bedard, C., Bremer, E., Graham, J. D., Chirico, D., & Cairney, J. (2021). Examining the effects of acute cognitively engaging physical activity on cognition in children. *Frontiers in Psychology, 12*, Article 653133. https://doi.org/10.3389/fpsyg.2021.653133

Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS One, 11*(12), Article e0167501. https://doi.org/10.1371/journal.pone.0167501

Benzing, V., & Schmidt, M. (2018). Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. *Journal of Clinical Medicine, 7*(11). https://doi.org/10.3390/jcm7110422

van den Berg, V., Saliasi, E., de Groot, R. H. M., Jolles, J., Chinapaw, M. J. M., & Singh, A. S. (2016). Physical activity in the school setting: Cognitive performance is not affected by three different types of acute exercise. *Frontiers in Psychology, 7*, 723. https://doi.org/10.3389/fpsyg.2016.00723

van den Berg, V., Saliasi, E., Jolles, J., de Groot, R. H. M., Chinapaw, M. J. M., & Singh, A. S. (2018). Exercise of varying durations: No acute effects on cognitive performance in adolescents. *Frontiers in Neuroscience, 12*, 672. https://doi.org/10.3389/fnins.2018.00672

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review, 30*(4), 331–351. https://doi.org/10.1016/j.dr.2010.08.001

Best, J. R. (2012). Exergaming immediately enhances children's executive function. *Developmental Psychology, 48*(5), 1501–1510. https://doi.org/10.1037/a0026648

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise, 14*(5), 377–381.

Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry, 25*(1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Brinkhuis, M. A. B., Kristjànsson, A., Harvey, B. M., & Brascamp, J. W. (2020). Temporal characteristics of priming of attention shifts are mirrored by bold response patterns in the frontoparietal attention network. *Cerebral Cortex, 30*, 2267–2280. https://doi.org/10.1093/cercor/bhz238

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*(2), 219–223. https://doi.org/10.1016/j.neulet.2008.06.024

Chang, Y. K., Chu, C. H., Wang, C. C., Wang, Y. C., Song, T. F., Tsai, C. L., & Etnier, J. L. (2015). Dose-response relation between exercise duration and cognition. *Medicine & Science in Sports & Exercise, 47*(1), 159–165. https://doi.org/10.1249/MSS.0000000000000383

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research, 1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Chang, Y. K., Pesce, C., Chiang, Y. T., Kuo, C. Y., & Fong, D. Y. (2015). Antecedent acute cycling exercise affects attention control: An ERP study using attention network test. *Frontiers in Human Neuroscience, 9*, 156. https://doi.org/10.3389/fnhum.2015.00156

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34–48. https://doi.org/10.1016/j.dcn.2015.11.005

Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P. D., Lambourne, K., & Szabo-Reed, A. N. (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine & Science in Sports & Exercise, 48*(6), 1223–1224. https://doi.org/10.1249/MSS.0000000000000966

Egger, F., Conzelmann, A., & Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychology of Sport and Exercise, 36*, 178–186. https://doi.org/10.1016/j.psychsport.2018.02.014

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149.

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition, 70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Flynn, R. M., & Richert, R. A. (2018). Cognitive, not physical, engagement in video gaming influences executive functioning. *Journal of Cognition and Development, 19*(1), 1–20. https://doi.org/10.1080/15248372.2017.1419246

Gallotta, M. C., Emerenziani, G. P., Franciosi, E., Meucci, M., Guidetti, L., & Baldari, C. (2015). Acute physical activity and delayed attention in primary school students. *Scandinavian Journal of Medicine & Science in Sports, 25*(3), 331–338. https://doi.org/10.1111/sms.12310

Gallotta, M. C., Guidetti, L., Franciosi, E., Emerenziani, G. P., Bonavolontà, V., Baldari, C., & Bonavolonta, V. (2012). Effects of varying type of exertion on children's attention capacity. *Medicine & Science in Sports & Exercise, 44*(3), 550–555. https://doi.org/10.1249/MSS.0b013e3182305552

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport, 21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Herold, F., Hamacher, D., Schega, L., & Müller, N. G. (2018). Thinking while moving or moving while thinking - concepts of motor-cognitive training for cognitive performance enhancement. *Frontiers in Aging Neuroscience, 10*, 228. https://doi.org/10.3389/fnagi.2018.00228

Herold, F., Müller, P., Gronwald, T., & Müller, N. G. (2019). Dose-Response Matters! - a perspective on the exercise prescription in exercise-cognition research. *Frontiers in Psychology, 10*, 2338. https://doi.org/10.3389/fpsyg.2019.02338

Herold, F., Törpel, A., Hamacher, D., Budde, H., Zou, L., Strobach, T., Müller, N. G., & Gronwald, T. (2021). Causes and consequences of interindividual response variability: A call to apply a more rigorous research design in acute exercise-cognition studies. *Frontiers in Physiology, 12*, Article 682891. https://doi.org/10.3389/fphys.2021.682891

Hwang, J., Hillman, C. H., Lee, I. M., Fernandez, A. M., & Lu, A. S. (2021). Comparison of inhibitory control after acute bouts of exergaming between children with obesity and their normal-weight peers. *Games for Health Journal, 10*(1), 63–71. https://doi.org/10.1089/g4h.2020.0018

Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C. M. (2014). Cognitive and physiological effects of an acute physical activity intervention in elementary school children. *Frontiers in Psychology, 5*, 71. https://doi.org/10.3389/fpsyg.2014.01473

Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C. M. (2015). The effects of qualitatively different acute physical activity interventions in real-world settings on executive functions in preadolescent children. *Mental Health and Physical Activity, 9*, 1–9. https://doi.org/10.1016/j.mhpa.2015.05.002

Ketelhut, S., Röglin, L., Martin-Niedecken, A. L., Nigg, C. R., & Ketelhut, K. (2022). Integrating regular exergaming sessions in the exercube into a school setting increases physical fitness in elementary school children: A randomized controlled trial. *Journal of Clinical Medicine, 11*(6). https://doi.org/10.3390/jcm11061570

Kowalski, K. C., Crocker, P. R. E., & Faulkner, R. A. (1997). Validation of the physical activity questionnaire for older children. *Pediatric Exercise Science, 9*(2), 174–186. https://doi.org/10.1123/pes.9.2.174

Koziol, L. F., Budding, D., Andreasen, N., D'Arrigo, S., Bulgheroni, S., Imamizu, H., Ito, M., Manto, M., Marvel, C., Parker, K., Pezzulo, G., Ramnani, N., Riva, D., Schmahmann, J., Vandervert, L., & Yamazaki, T. (2014). Consensus paper: The cerebellum's role in movement and cognition. *The Cerebellum, 13*(1), 151–177. https://doi.org/10.1007/s12311-013-0511-x

Kristjànsson, A., & Àsgeirsson, A. G. (2019). Attentional priming: Recent insights and current controversies. *Current Opinion in Psychology, 29*, 71–75. https://doi.org/10.1016/j.copsyc.2018.11.013

Kruijne, W., & Meeter, M. (2015). The long and the short of priming in visual search. Attention, Perception. *Psycho, 77*, 1558–1573. https://doi.org/10.3758/s13414-015-0860-2

Lamb, K. L. (1996). Exercise regulation during cycle ergometry using the children's effort rating table (CERT) and rating of perceived exertion (RPE) scales. *Pediatric Exercise Science, 8*(4), 337–350. https://doi.org/10.1123/pes.8.4.337

Lambourne, K., & Tomporowski, P. D. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research, 1341*, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091

Léger, L. A., Mercier, D., Gadoury, C., & Lambert, J. (1988). The multistage 20 meter shuttle run test for aerobic fitness. *Journal of Sports Sciences, 6*, 93–101.

Li, Y., Wang, Y., Jin, X., Niu, D., Zhang, L., Jiang, S. Y., Ruan, H. D., & Ho, G. W. (2021). Sex differences in hemispheric lateralization of attentional networks. *Psychological Research, 85*(7), 2697–2709. https://doi.org/10.1007/s00426-020-01423-z

Lubans, D. R., Leahy, A. A., Mavilidi, M. F., & Valkenborghs, S. R. (2022). Physical activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. *Current Topics in Behavioral Neurosciences, 53*, 103–130. https://doi.org/10.1007/7854_2021_271

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Puhse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology, 53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736

Macleod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the attention network test. *Neuropsychology, 24*(5), 637–651. https://doi.org/10.1037/a0019803

Martin-Niedecken, A. L., Mahrer, A., Rogers, K., de Bruin, E. D., & Schättin, A. (2020). HIIT" the ExerCube: Comparing the effectiveness of functional high-intensity interval training in conventional vs. exergame-based training. *Frontiers of Computer Science, 2*. https://doi.org/10.3389/fcomp.2020.00033. Article 33.

Martin-Niedecken, A. L., Rogers, K., Turmo Vidal, L., Mekler, E. D., & Márquez Segura, E. (2019). Exercube vs. Personal trainer. In S. Brewster (Ed.), *ACM digital library, proceedings of the 2019 CHI conference on human factors in computing systems* (pp. 1–15). Association for Computing Machinery. https://doi.org/10.1145/3290605.3300318.

Moreau, D., & Chou, E. (2019). The acute effect of high-intensity exercise on executive function: A meta-analysis. *Perspectives on Psychological Science, 14*(5), 734–764. https://doi.org/10.1177/1745691619850568

Moriarty, T. A., Mermier, C., Kravitz, L., Gibson, A., Beltz, N., & Zuhl, M. (2019). Acute aerobic exercise based cognitive and motor priming: Practical applications and mechanisms. *Frontiers in Psychology, 10*, 2790. https://doi.org/10.3389/fpsyg.2019.02790

Otero, T. M., Barker, L. A., & Naglieri, J. A. (2014). Executive function treatment and intervention in schools. *Applied Neuropsychology. Child, 3*(3), 205–214. https://doi.org/10.1080/21622965.2014.897903

Paschen, L., Lehmann, T., Kehne, M., & Baumeister, J. (2019). Effects of acute physical exercise with low and high cognitive demands on executive functions in children: A systematic review. *Pediatric Exercise Science, 31*(3), 267–281. https://doi.org/10.1123/pes.2018-0215

Pesce, C. (2009). An integrated approach to the effect of acute and chronic exercise on cognition: The linked role of individual and task constraints. In T. McMorris, P. D. Tomporowski, & M. Audiffren (Eds.), *Exercise and cognitive function*. Wiley-Heinrich.

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport & Exercise Psychology, 34*(6), 766–786. https://doi.org/10.1123/jsep.34.6.766

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise, 40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Preckel, F. (2014). Assessing need for cognition in early adolescence. *European Journal of Psychological Assessment, 30*(1), 65–72. https://doi.org/10.1027/1015-5759/a000170

Schmidt, M., Benzing, V., & Kamer, M. (2016). Classroom-based physical activity breaks and children's attention: Cognitive engagement works. *Frontiers in Psychology, 7*, 1474. https://doi.org/10.3389/fpsyg.2016.01474

Schmidt, M., Egger, F., Anzeneder, S., & Benzing, V. (2021). Acute cognitively challenging physical activity to promote children's cognition. In R. Bailey (Ed.), *ICSSPE perspectives. Physical activity and sport during the first ten years of life: Multidisciplinary perspectives* (pp. 141–155). Routledge.

Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review, 120*(3), 439–471. https://doi.org/10.1037/a0033138

Tomporowski, P. D., McCullick, B., Pendleton, D. M., & Pesce, C. (2015). Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science, 4*(1), 47–55. https://doi.org/10.1016/j.jshs.2014.09.003

Torsheim, T., Cavallo, F., Levin, K. A., Schnohr, C., Mazur, J., Niclasen, B., & Currie, C. (2016). Psychometric validation of the revised family affluence scale: A latent variable approach. *Child Indicators Research, 9*(3), 771–784. https://doi.org/10.1007/s12187-015-9339-x

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *British Journal of Sports Medicine, 48*(12), 973–979. https://doi.org/10.1136/bjsports-2012-091441

Watzlawik, M. (2009). Die Erfassung des Pubertätsstatus anhand der Pubertal Development Scale. *Diagnostica, 55*(1), 55–65. https://doi.org/10.1026/0012-1924.55.1.55

Wen, X., Yang, Y., & Wang, F. (2021). Influence of acute exercise on inhibitory control and working memory of children: A comparison between soccer, resistance, and coordinative exercises. *International Journal of Sport Psychology*, (52), 101–119. https://doi.org/10.7352/IJSP.2021.52.101