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Dose–response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition

Sofia Anzeneder[1] | **Cäcilia Zehnder**[1] | **Jürg Schmid**[1] | **Anna Lisa Martin-Niedecken**[2] | **Mirko Schmidt**[1] | **Valentin Benzing**[1]

[1]Institute of Sport Science, University of Bern, Bern, Switzerland

[2]Department of Design, Zurich University of the Arts, Zurich, Switzerland

Correspondence
Sofia Anzeneder, Institute of Sport Science, University of Bern, Bern, Switzerland.
Email: sofia.anzeneder@unibe.ch

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Abstract

Acute bouts of physical exercise have the potential to benefit children's cognition. Inconsistent evidence calls for systematic investigations of dose–response relations between quantitative (intensity and duration) and qualitative (modality) exercise characteristics. Thus, in this study the optimal duration of an acute cognitively challenging physical exercise to benefit children's cognition was investigated, also exploring the moderating role of individual characteristics. In a within-subject experimental design, 104 children ($M_{age}=11.5$, $SD=0.8$, 51% female) participated weekly in one of four exergaming conditions of different durations (5, 10, 15, 20 min) followed by an Attention Network task (ANT-R). Exergame sessions were designed to keep physical intensity constant (65% HR_{max}) and to have a high cognitive challenge level (adapted to the individual ongoing performance). Repeated measures ANOVAs revealed a significant effect of exercise duration on reaction times (RTs; $p=0.009$, $\eta^2_p=0.11$), but not on response accuracy. Post hoc analyses showed faster information processing speed after 15 min of exercise compared to 10 min ($p=0.019$, $\eta^2_p=0.09$). Executive control, alerting and orienting performances and interactions were unaffected by exercise duration ($p_s > 0.05$). Among individual characteristics, habitual physical activity moderated duration effects on RTs. For more active children, exercise duration influenced the interaction between executive control and orienting ($p=0.034$; $\eta^2_p=0.17$) with best performances after the 15 min duration. Results suggest that an acute 15 min cognitively high-challenging bout of physical exercise enhances allocable resources, which in turn facilitate information processing, and—for more active children only—also executive processes. Results are interpreted according to the arousal theory and cognitive stimulation hypothesis.

Mirko Schmidt and Valentin Benzing share senior authorship.

KEYWORDS
acute physical activity, Attention Network task, cognitive engagement, executive function, exergaming, inhibition

1 | INTRODUCTION

Acute physical exercise (i.e., a single bout of exercise) has the potential to transiently enhance subsequent cognitive performance,[2,3] especially in children.[4] Cognitive benefits of acute physical exercise are largely influenced by the interaction of quantitative (duration, intensity) and qualitative exercise characteristics (modality),[5,6] as well as by the responsiveness of individuals with different characteristics (e.g., environmental, developmental, physical, and cognitive).[1,7] Chronic cognitively challenging physical exercise, which elicits cognitive engagement,[†] appears to have positive effects on children's cognition.[9] Concerning immediate after-effects of an acute cognitively challenging physical exercise, however, results are inconsistent.[10,11] It is still unclear which duration of cognitively challenging bouts of physical exercise benefits cognition the most. This is of great practical importance in the educational setting for designing active breaks to enhance cognitive functions essential for learning and academic achievement, such as attention and executive functions (EFs). While attention encompasses different processes related to how the organisms becomes receptive to internal and external stimuli and how it begins to process them,[12] EFs refer to higher-level functions that enable self-regulation and goal-directed behavior.[13]

A function at the intersection between the broad and multifaceted constructs of attention and EFs is executive control, that is, the ability to exert control over interference. Executive control is a component of inhibition, along with response inhibition (suppressing or resisting automatic responses) and cognitive inhibition (suppressing thoughts and memories).[13] It 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).[14,15]

Meta-analyses revealed that acute physical exercise has positive effects on children's executive control with ES ranging from 0.28 to 0.57.[16,17] Although these positive results seem relatively consistent, there is considerable heterogeneity in the magnitude of effects.[5] Therefore, research increasingly focused on dose–response relationships between exercise characteristics, cognitive outcomes, and underlying mechanisms. The dose–response relation in children and adolescents has been mostly investigated by manipulating exercise intensity and less frequent exercise duration.[2,5,18] Correspondingly, while meta-analytic findings suggest that bouts of physical exercise with at least moderate intensity are most beneficial for EFs (when cognitive performance is assessed following a delay of more than 1 min)[2,5] with no differences between moderate and vigorous intensities,[18] they do not allow to univocally identify an optimal exercise duration.[16,17] Furthermore, the few child and adolescent studies that have manipulated the duration of acute bouts of physical exercise are hardly comparable due to differences in both exercise intensity and modality.[19–22] Differences in modality, such as in cognitive challenge and related cognitive engagement, are thought to contribute to exercise effects on cognitive performance.[6]

Therefore, increasing research investigated qualitative exercise characteristics such as the cognitive challenge level.[10,11] However, no acute cognitively challenging exercise studies manipulated bout duration. In children and adolescents, acute cognitively challenging exercise studies showed a mixed pattern of results.[10,11] In the duration range most frequently used (10–20 min), acute cognitively challenging bouts of physical exercise at moderate to vigorous intensity resulted in facilitation,[23–27] no effects,[28–31] or even detrimental effects on cognition.[32] Conversely, longer exercise durations (40 and 50 min) elicited either no effects or detrimental effects, respectively.[33–35] A univocal synthesis of the above studies is limited by the variety of modalities used. To identify optimal exercise characteristics for children's cognition, further research that systematically investigates the effects of acute cognitively challenging exercise of different durations on attention and EFs, holding modality constant, is needed.

Moreover, the pattern of moderators acting on the acute exercise-cognition relation is complexified by the individual responsiveness to physical and cognitive challenges of bouts of physical exercise.[1,7] Previous evidence recommends to finely tune exercise demands to children's developmental level and expertise[36] as well as to their physical and cognitive abilities.[4,7,37] Depending on these abilities, the combination of acute exercise's varying physical and cognitive demands may be under- or over-challenging.[11,32]

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*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).[1]

[†] To distinguish it from behavioral and emotional engagement, cognitive engagement can be defined as the degree to which the allocation of attentional resources and cognitive effort is needed to master difficult skills.[8]

In sum, to design acute bouts of physical exercise for children that transiently enhance cognitive function, it is essential to consider dose–response relations within the frame of quantitative and qualitative exercise characteristics, as well as the individual responsiveness to acute bouts of physical exercise.

Thus, the *first aim* of the present study was to investigate which duration of an acute cognitively challenging bout of physical exercise benefits children's executive control the most. Considering that studies investigating single durations of cognitively challenging bouts of physical exercise led to inconsistent evidence in the 10–20 min range,[11] we investigated multiple durations up to 20 min. In line with overall meta-analytic findings across the lifespan, showing that neither shorter (e.g., 5 min)[2] nor longer duration (e.g., 20 min)[38] of acute physical exercise benefits cognition, we hypothesized that intermediate durations (10 and 15 min) would elicit larger executive control gains compared to shorter and longer ones. The *second aim* was to investigate whether the duration of an acute cognitively challenging bout of physical exercise affects not only executive control, but also alerting and orienting performances, as well as their interactive functioning (i.e., the effect of alerting or orienting on executive control efficiency[14]), which in turn seem to underlie cognitive and emotional control processes relevant for academic learning.[39] However, considering that acute physical exercise studies addressing after-effects on alerting and orienting are limited and inconsistent[22,40] and none investigated the interaction among attention networks, no a priori hypothesis was stated. The *third exploratory aim* was to evaluate whether individual characteristics interact with exercise duration. Given the limited evidence on the moderating role of individual characteristics regarding the effects of acute cognitively challenging bouts of physical exercise,[11,36] no a priori hypothesis was stated, and a wide range of environmental, developmental, physical, and cognitive characteristics were included in these exploratory analyses.

2 | METHODS

This study was part of the project "School-based physical activity and children's cognitive functioning: The quest for theory-driven interventions." The project aims to investigate the effects of qualitative and quantitative characteristics of designed, school-based, bouts of physical exercise on children's cognitive functions. The project was preregistered 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

One hundred four children aged 10–13 years ($M = 11.5$, $SD = 0.8$; 51% female) were recruited from three primary schools in the region of Bern, Switzerland. The legal guardians of all children provided informed written consent and children agreed to participate. Exclusion criteria were any neurological, developmental, or medical condition that would affect the subjects' integrity or study results. We conducted a power analysis using the SuperPower Shiny app (https://shiny.ieis.tue.nl/anova_power/) to determine sample size. We defined a within-subjects design with four exercise duration conditions and estimated effects based on previous studies[23,25,29] with alpha error probability = 0.05 and correlation between the repeated measures $r = 0.61$. We assumed that children's executive control performance (as difference value, see "Cognitive measures" section) would be faster after the 10 min ($M = 100$ ms, $SD = 80$) and 15 min conditions ($M = 100$ ms, $SD = 80$; with no significant differences between the 10 min and 15 min conditions), compared to the 5 min ($M = 125$ ms, $SD = 80$) and 20 min ones ($M = 125$ ms, $SD = 80$; with no significant differences between the 5 min and 20 min conditions). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed a power of 99% for repeated measures ANOVAs and more interestingly a power of > 80% for Bonferroni-adjusted *t*-test comparisons (6 comparisons) of above hypothesized significant differing conditions (5 vs. 10 min, 5 vs. 15 min, 10 vs. 20 min, 15 vs. 20 min).

Of the 114 participants initially recruited, four were injured during the intervention period outside the study (e.g., at home) and six were identified as multivariate outliers based on Mahalanobis distance ($p < 0.001$), and were therefore excluded. Due to technical problems with the tablets used for attentional testing (SurfTab 10.1; TrekStor GmgH), there was some loss of data (3.1%). Since Little's MCAR test has led to a non-significant result ($p = 0.986$), 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-subjects crossover design study with counterbalanced order of experimental conditions (24 possible permutations), the duration of an acute cognitively challenging, exergame-based, bout of physical exercise was manipulated to be 5, 10, 15, or 20 min (C5, C10, C15, C20).

The study was conducted over a period of 5 weeks. During the first study week, data were collected on two separate days. On the first day, background characteristics were assessed by a questionnaire, including age, biological sex, height, weight, socioeconomic status, pubertal developmental status, habitual physical activity, need for cognition, and weekly videogame practice. Subsequently, children performed a 20-m Shuttle Run test to assess their maximum heart rate (HR) and fitness level. Acceptable reliability and validity were demonstrated for background variables; only the videogame practice questionnaire was self-developed for the purposes of the current study (for a detailed description and references of background variables see Appendix S1). At the second visit, children participated in a familiarization session. Each child completed a specifically developed tutorial of the exergame. Gameplay (each movement) was explained and the exergame continued only when movements were carried out correctly. After the tutorial, children participated in a 3 min regular version of the exergame. Subsequently, to familiarize children with attentional testing, they performed the practice block of the cognitive tests (for details, see "Cognitive measures").

TABLE 1 Participant's background variables.

Background variables	*M* (*SD*)
Age (years)	11.5 (0.8)
Biological sex (% female)	51%
Socioeconomic status [2–14]	8.4 (2.1)
Body mass index (kg/m^2)	18.7 (3.3)
Pubertal developmental status [3–12]	5.8 (2.2)
Habitual physical activity [1–5]	2.6 (0.5)
VO_{2max} (mL/kg/min)	51.5 (6.8)
Weekly videogame practice (min)	194.7 (237.4)
Need for cognition [19–95]	62.2 (12.6)

Children played one exergaming session per week between the second and fifth week. Before, during, and after the exergame, manipulation check and control variables were collected. These measures have acceptable reliability and validity (for a detailed description and references see Appendix S1). During the exergaming task, HR was continously monitored. Each session included a short assessment before exergaming, 2 min warm-up, 5–20 min of exergaming (depending on condition) intermitted by short assessment breaks every 5 min, a short assessment immediately after exergaming, a water break, and the

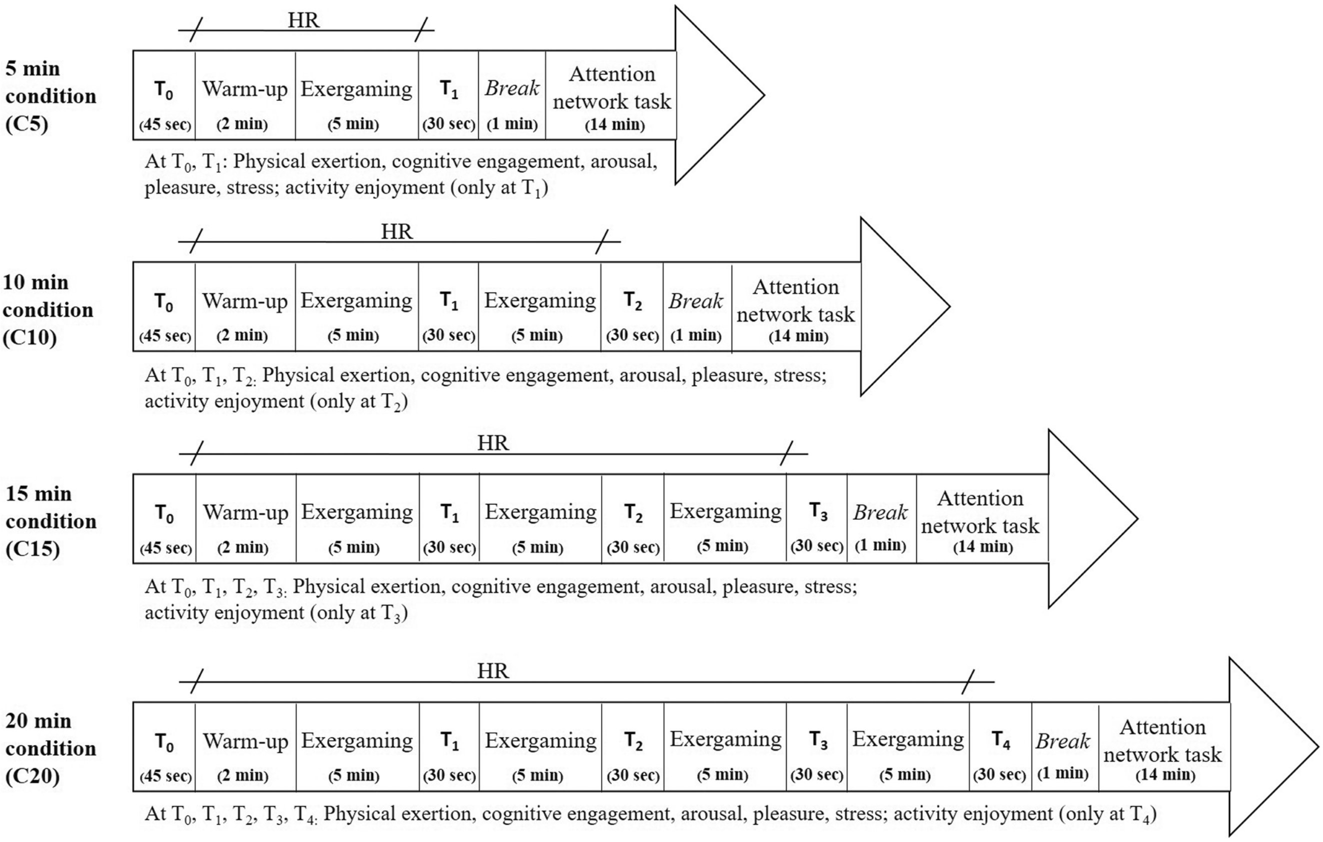


FIGURE 1 Experimental protocol of the weekly sessions (which were carried out in a counterbalanced order). *Note*: T = assessment times; T_0 = before activity (pre); T_1 = after 5 min activity; T_2 = after 10 min activity; T_3 = after 15 min activity; T_4 = after 20 min activity; HR = heart rate.

subsequent attentional testing with the revised Attention Network task (ANT-R).[14] In total, C5, C10, C15, and C20 sessions lasted about 23 min, 29 min, 34 min, and 40 min, respectively. The experimental protocol and timeline of the respective weekly session are depicted in Figure 1. While children were blinded to the conditions, assessors were not, since they had to stop the exergaming after 5, 10, 15, and 20 min, respectively. However, the ANT-R is a highly standardized tablet-based test.[14] Thus, assessors most probably did not bias the cognitive outcome measure.

2.3 | Intervention and experimental conditions

We used an exergame in the school setting to manipulate and individualize both physical and cognitive exercise challenges in a highly controlled and ecologically valid fashion. Exergaming refers to active video gaming that embeds gross-motor exercise into videogame play.[41] The exergame sessions took place during school hours and were performed individually, once weekly, at the same time and day each week. The intervention consisted of a modified version of the exergame Sphery Racer.[42] To control the exergame, participants performed different functional workout movements (e.g., jumps, squats, or punches) while being immersed in a rapid underwater race game scenario. In this game scenario, they navigated an avatar and passed various colored gates, which provided them with information regarding respective functional workout movements and cognitive tasks to be performed. During the exergame session, participants wore four motion-based trackers (HTC Vive tracking sensors, Vive) attached to their wrists and ankles as well as an HR sensor (Polar Team2 straps and transmitters; Polar Electro) to constantly track their movements and body position, and their HR, respectively. The physical intensity was held constant during the session at approximately 65% HR_{max}. Most of the previous research in this area investigated moderate to vigorous intensities,[3] showing beneficial effects.[4,43,44] Therefore, a similar intensity was chosen for comparability reasons and to avoid overload because of the potential combined effects of physical intensity and cognitive challenge. The cognitive challenge level of the exergame was chosen according to the results of a previous study,[45] showing that a high-challenging bout enhanced children's executive control more than less challenging versions of the same exergame. Jumps, squats, skipping, and deep lunges were used to maintain HR constant (50% of total movements) while punches and catching sideway points were used to manipulate the cognitive challenge (50% of total movements). The latter, more cognitively challenging movements, were designed to mirror attentional allocation processes involved in the ANT-R paradigm (see "Cognitive measures" section). The tasks included anticipatory cues that alerted and oriented attention and targets that required movement actions while ignoring distracting stimuli (for details on exergaming tasks see description and video in Appendix S2). During the exergame session, the level of cognitive challenge was constantly adapted to the individual ongoing performance. The task was rendered easier or more difficult if the participant made more or less than three errors in a period of 30 seconds, respectively. Task difficulty was modulated by an ascending number of distracting stimuli (40%–60%) and misleading cues (13%–19%), which preceded punches and lateral shuffle steps (i.e., catching sideway points).

2.4 | Manipulation check

Several variables were assessed to test whether experimental manipulation had succeeded (see Figure 1). PolarTeam2 belts and transmitters were used to measure *children's HR* during exergaming (measurement every 3 seconds) and to adjust the physical intensity at 65% HR_{max}. In addition, *perceived physical exertion* (RPE) and *cognitive engagement* (RCE) were measured using the Borg RPE and the adapted RCE scales (for a detailed description and references see Appendix S1).

2.5 | Control variables

According to previous evidence highlighting that affective states elicited by acute exercise need to be considered,[27,28] several control variables were assessed (see Figure 1). *Arousal*, *pleasure*, and *perceived stress* were assessed using the single-item pictorial Self-Assessment-Manikin, and *enjoyment* with the physical activity enjoyment scale (for a detailed description and references see Appendix S1).

2.6 | Cognitive measures

A child-adapted version of the ANT-R[14] was used on Inquisit 5 (Millisecond Software) to assess the efficiency of (a) *executive control* (primary outcome), (b) *alerting* and *orienting networks*, and (c) the *influence of alerting and orienting networks on executive control*. For the primary outcome, a retest reliability ranging from 0.61 to 0.71 has been shown.[46]

To capture the functioning of attention network systems, the test combines the Attention cueing paradigm that assesses alerting and orienting, and the Flanker task 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 in which a subsequent target most probably will appear. An invalid spatial cue indicates the opposite location. Subsequently, a congruent or incongruent flanker condition appears. The child's task is to identify the direction of the center arrow by pressing a right or left button, while ignoring lateral flanker arrows. Reaction times (RTs) and response accuracy are recorded. The task is composed of 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 one-min break between blocks. Responses with RTs faster than 200 ms or longer than 1700 ms were excluded automatically.[14] Further details on the task parameters and cue-target interval timing can be found elsewhere.[14] 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 are better able to 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* is composed of *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 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] – [valid spatial cue trials with incongruent flanker – valid spatial cue trials with congruent flanker]). The effect of *disengaging* is calculated as ([invalid spatial cue trials with incongruent flanker – invalid spatial 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 a validly oriented attention on executive control. Instead, for *disengaging*, a positive value indicates the cost of an invalidly oriented attention.

2.7 | Statistical analyses

All analyses were performed using SPSS version 27.0 (SPSS Inc.). Preliminary analyses were run using repeated measures ANOVAs for the comparison of manipulation check (RPE, RCE) and control variables (arousal, pleasure, stress) among exergaming time (Pre, During, and Post; see Figure 1) separately for each duration condition (C5, C10, C15, C20). Subsequent ANOVAs were run for the comparison of manipulation check and control variables among conditions at Pre to test for baseline differences. If baseline differences emerged, ANOVAs to test for the effect of duration were performed using (Post – Pre) delta scores in absolute value. Analyses were performed as well on delta scores in relative value ([Post – Pre]/Pre and [Post – Pre]/[Post + Pre]) and results depicted scores in absolute value. Further ANOVAs were run for the comparison among duration conditions (C5, C10, C15, C20) of (a) HR average during exergaming and (b) activity enjoyment after exergaming. Post hoc Bonferroni-adjusted pairwise comparisons for the effect of duration are reported.

To analyze the effect of duration on overall RTs and response accuracy as a function of attentional factors (cue and flanker conditions that depict attention network performances), a 4 (duration conditions) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVAs were performed, separately for RTs and response accuracy. Post-hoc Bonferroni-adjusted pairwise comparisons were reported for the effect of duration.

To explore the moderating role of individual characteristics (age, sex, socioeconomic status, BMI, pubertal status, habitual physical activity, VO_2max, videogame practice, need for cognition) on the effect of exercise duration on attention networks, continuous individual background variables were first dichotomized (i.e., median split). Subsequently, they were included as categorical moderators in ANOVAs on RT and accuracy difference values reflecting attention network performances and interactions (RT and accuracy under the different cue and flanker conditions were reduced in a theory-based manner; see "Cognitive measures" section). In the case of significant interactions including potential moderators, performances after the four duration conditions were contrasted by means of post-hoc ANOVAs, separately for each group of children (e.g., low and high habitual physical activity), and subsequent Bonferroni-adjusted pairwise comparisons.

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 performed also on mean RTs, with and without the six multivariate outliers. Results depict median RTs with multivariate outliers excluded. The level of significance was set at $p<0.05$ for all analyses, and η^2_p was reported as an estimation of effect size (small effect size = 0.01, medium effect size = 0.06, large effect size = 0.14).

3 | RESULTS

3.1 | Manipulation check

Statistics of manipulation check variables among duration conditions (C5, C10, C15, C20) and time points (Pre, During, Post) are presented in Appendix S3. First ANOVAs, performed separately for each duration condition (C5, C10, C15, C20), revealed in all conditions a significant effect of time on RPE ($p_s < 0.001$; $\eta^2_{ps} > 0.63$) and RCE ($p_s < 0.001$; $\eta^2_{ps} > 0.41$). Further ANOVAs on delta scores (Post − Pre) among duration conditions revealed a significant effect of duration for RPE (duration: F (3, 101) = 5.16, $p = 0.002$, $\eta^2_p = 0.13$) and RCE (duration: F (3, 101) = 6.02, $p = 0.001$, $\eta^2_p = 0.15$). As concerns the effect of duration, Bonferroni-adjusted pairwise comparisons showed that C5 was perceived as less physically exerting and cognitively engaging compared to C15 (RPE: $p = 0.006$, $\eta^2_p = 0.10$; RCE: $p = 0.004$, $\eta^2_p = 0.11$) and C20 (RPE: $p = 0.003$, $\eta^2_p = 0.11$; RCE: $p = 0.001$, $\eta^2_p = 0.13$), whereas the shortest (C5 vs. C10) and longest conditions (C15 vs. C20) were perceived as equally demanding ($p_s > 0.999$, $\eta^2_{ps} < 0.01$; see Appendix S3). The difference in RPE among conditions was not paralleled by objective HR data ($p = 0.403$; $\eta^2_p = 0.03$), which was designed to be similar across conditions.

3.2 | Control variables

Statistical analyses of control variables among duration conditions (C5, C10, C15, C20) and time points (T_0, T_1, T_2, T_3, T_4) are presented in Appendix S3. First ANOVAs, performed separately for each duration condition (C5, C10, C15, C20), showed in all conditions a significant effect of time on arousal ($p_s < 0.001$; $\eta^2_{ps} > 0.17$). Similar ANOVAs on perceived pleasure revealed only in C20 a significant decrease over time ($p = 0.008$, $\eta^2_p = 0.13$) with no differences from Pre to Post in other duration conditions ($p_s > 0.123$; $\eta^2_{ps} < 0.03$). Further separate ANOVAs on perceived stress showed in C10, C15 and C20 a significant effect of time ($p_s = 0.001$; $\eta^2_{ps} > 0.14$) with no differences from Pre to Post in C5 ($p = 0.109$, $\eta^2_p = 0.03$).

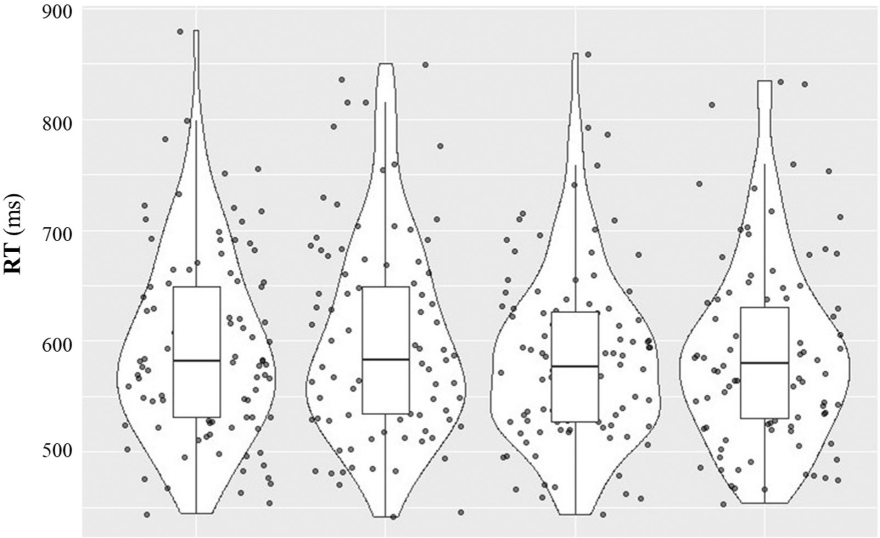
Further ANOVAs on delta scores (Post − Pre) of control variables revealed an effect of duration (with medium effect size) on stress (F (3, 101) = 2.58, $p = 0.058$, $\eta^2_p = 0.07$), but no significant effects on arousal (F (3, 101) = 0.78, $p = 0.504$, $\eta^2_p = 0.02$) or pleasure (F (3, 101) = 0.14, $p = 0.936$, $\eta^2_p = 0.00$). As concerns the effect of duration on stress, Bonferroni-adjusted pairwise comparisons showed that C20 was perceived as more stressful than C5 ($p = 0.058$, $\eta^2_p = 0.06$), whereas other conditions were perceived as equally stressful ($p_s > 0.182$, $\eta^2_{ps} < 0.04$; see Appendix S3). The difference in perceived stress among conditions was paralleled by enjoyment data (duration: F (3, 101) = 4.10, $p = 0.009$, $\eta^2_p = 0.11$), which showed that C20 was perceived as less enjoyable than C5 ($p = 0.004$, $\eta^2_p = 0.11$) and C10 ($p = 0.074$, $\eta^2_p = 0.06$), whereas other conditions were perceived as equally enjoyable ($p_s > 0.136$, $\eta^2_{ps} < 0.05$).

3.3 | Cognitive measures

3.3.1 | Effects of duration on executive control, alerting, orienting, and their interactions

A first ANOVA on RTs revealed the classic cue (F (3, 101) = 411.62, $p < 0.001$, $\eta^2_p = 0.92$), flanker (F (1, 103) = 589.93, $p < 0.001$, $\eta^2_p = 0.85$) and cue × flanker effects (F (3, 101) = 37.03, $p < 0.001$, $\eta^2_p = 0.52$), which are well known in the literature.[14]

As regard the first two aims, a significant effect of duration on overall RTs with a medium to large effect (F (3, 101) = 4.04, $p = 0.009$, $\eta^2_p = 0.11$), but no further interaction effects of duration with flanker (i.e., the effect of duration on executive control; F (3, 101) = 0.21, $p = 0.890$, $\eta^2_p = 0.01$), cue (i.e., the effect of duration on alerting and orienting; F (3, 101) = 0.91, $p = 0.520$, $\eta^2_p = 0.08$), or cue × flanker (i.e., the effect of duration on attention networks' interactions; F (9, 95) = 0.86, $p = 0.560$, $\eta^2_p = 0.08$) emerged. Results show



C5	C10	C15	C20
M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
593.93 (8.1)	599.18 (8.7)	584.29 (7.6)	588.17 (8.0)

FIGURE 2 Effects of duration on overall reaction times (RTs). *Note*: Duration: $F(3, 101)=4.04$, $p=0.009$, $\eta^2_p=0.11$. C5 = 5 min condition, C10 = 10 min condition, C15 = 15 min condition, C20 = 20 min condition. Results of post-hoc comparisons (significant results bolded): C5 vs. C10: $p=1.00$, $\eta^2_p=0.01$. C5 vs. C15: $p=0.310$, $\eta^2_p=0.04$. C5 vs. C20: $p=1.00$, $\eta^2_p=0.01$. **C10 vs. C15: $\boldsymbol{p=0.019}$, $\boldsymbol{\eta^2_p=0.09}$**. C10 vs. C20: $p=0.210$, $\eta^2_p=0.04$. C15 vs. C20: $p=1.00$, $\eta^2_p=0.01$.

that the duration condition influenced subsequent overall RTs, but not specifically attention network performances and interactions. Post hoc Bonferroni-adjusted pairwise comparisons revealed significant faster RTs after C15 compared to C10 ($p=0.019$, $\eta^2_p=0.09$), with small to medium effect size differences between C5 and C15 ($p=0.310$, $\eta^2_p=0.04$) and C10 and C20 ($p=0.211$, $\eta^2_p=0.04$; see Figure 2), but no differences between C5 and C10 and between C15 and C20 ($p_s=1.00$, $\eta^2_{ps}=0.01$). There were no effects of duration for accuracy (duration: $p=0.952$, $\eta^2_p=0.00$; duration × flanker: $p=0.439$, $\eta^2_p=0.03$; duration × cue: $p=0.451$, $\eta^2_p=0.09$; duration × cue × flanker: $p=0.775$, $\eta^2_p=0.06$).

3.3.2 | Moderating role of individual characteristics

ANOVAs on RT differences with dichotomized individual characteristics as between-subject factors revealed only for habitual physical activity level and only for the RT difference reflecting the interaction between executive control and spatial disengaging (component of orienting) a significant interaction effect of duration ($F(3, 100)=4.81$, $p=0.004$, $\eta^2_p=0.13$).[‡] Subsequent ANOVAs run on these RT differences, separately for children with lower and higher habitual physical activity levels, revealed only for children with higher physical activity levels a significant effect of duration ($F(3, 46)=3.15$, $p=0.034$, $\eta^2_p=0.17$). Post hoc Bonferroni-adjusted pairwise comparisons revealed lower disengaging costs for executive control after C15 compared to C5 ($p=0.040$, $\eta^2_p=0.08$) with no further differences among conditions ($p_s>0.060$, $\eta^2_{ps}<0.04$). To interpret this result in children with higher habitual physical activity levels, the difference between flanker effect under invalid spatial cue conditions and double cue conditions were computed separately. As indicated in Figure 3, after C15 lower disengaging costs for executive control resulted from faster RTs after invalid spatial cue conditions (decreasing dark orange bars, Figure 3), whereas after double cue conditions RTs remained stable among conditions (light orange bars, Figure 3). Same analyses performed on accuracy data were not significant ($p>0.060$, $\eta^2_p<0.07$).

No further interaction effects of duration with dichotomized individual characteristics emerged neither on RTs nor accuracy values reflecting executive control, alerting, orienting performances and their interactions ($ps>0.170$, $\eta^2_{ps}<0.05$).

4 | DISCUSSION

The first aim of the present study was to investigate the dose–response relation between different durations of a cognitively high-challenging bout of physical exercise (5, 10, 15, 20 min) and children's executive control performance. The second aim was to test executive control performance from an attention network perspective to

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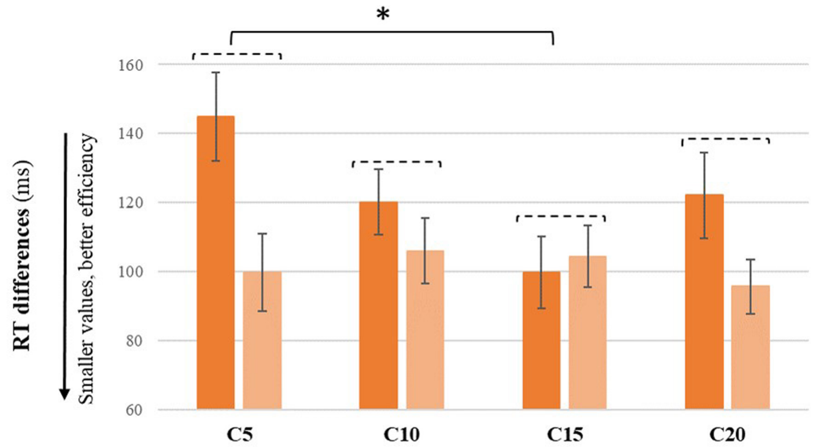
[‡] An anonymous reviewer validly pointed out, that dichotomization of continuous variables may incur potential difficulties. Thus, we performed subsequent multi-level analyses also with continuous individual variables. Results show similar trends for continuous as for dichotomized variables. Specifically, even if the interaction effect of bout duration and habitual physical activity level on the interactive functioning of executive control and spatial disengaging did not reach significance ($p=0.056$), results show a significant post-hoc difference between C15 and C5 ($p=0.006$), indicating that RT differences decreased with increasing habitual physical activity level.



	C5	C10	C15	C20
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
🟧 **Invalid spatial cue**	144.90 (12.85)	120.19 (9.58)	99.84 (10.42)	122.10 (12.39)
▨ **Double cue**	99.82 (11.27)	106.00 (9.43)	104.42 (9.03)	95.71 (7.86)

FIGURE 3 Effects of duration on the interaction of executive control (flanker effect) and orienting (spatial attention disengagement) in children with higher habitual physical activity levels. *Note*: C5 = 5 min condition, C10 = 10 min condition, C15 = 15 min condition, C20 = 20 min condition. Dark orange bars = flanker effect under invalid spatial cue conditions, computed as (Invalid spatial cue, flanker incongruent – Invalid spatial cue, flanker congruent). Light orange bars = flanker effect under double cue conditions, computed as (Double cue, flanker incongruent – Double cue, flanker congruent). Error bars represent the standard error of the mean. The interaction of executive control and disengaging is represented by differences between dark orange and light orange bars (dotted lines). Duration effect: F (3, 46) = 3.15, $p = 0.034$, $\eta^2_p = 0.17$. Significant difference: *C5 vs. C15: $p = 0.040$, $\eta^2_p = 0.08$. RT, reaction time.

further our understanding of acute exercise duration effects on the efficiency of executive control along and interacting with alerting and orienting attention networks. Finally, we explored if an optimal exercise duration varies according to individual characteristics. In sum, the 15 min bout of physical exercise benefited children's overall information processing speed the most, whereas the efficiency of executive control and other attention networks (alerting and orienting) was unaffected by the duration of the bout. However, exercise duration affected the interactive functioning of executive control and orienting networks in more active children, suggesting that the dose–response relation of interest may be moderated by children's habitual physical activity level. Specifically, more active children seem better able to capitalize on an optimal (15 min) acute exercise duration for maintaining executive control efficiency also under more complex spatial attention conditions.

The present study is the first to directly compare the acute effects of different durations of a cognitively challenging bout of physical exercise on children's executive control and on its functioning in interaction with other attention networks. Regarding the primary aim of the study, executive control performance was not differentially affected by the employed durations, which instead showed differential effects on overall RTs only, in line with previous acute exercise research with adolescents.[20] Indeed, the fine-grained analysis of different durations between 5 and 20 min allowed identifying the duration (15 min), within the intermediate range, that benefited information processing speed the most. In detail, children became faster while maintaining a high response accuracy, thus suggesting a benefit for RTs without a speed-accuracy trade-off effect. This likely reflects the transient biochemical and neurophysiological changes that underlie altered psychological states, such as increased arousal, which facilitate performance in subsequent cognitive tasks.[5]

As regard duration effects in acute exercise studies, to the best of our knowledge, only two studies manipulated the duration of an acute bout of physical exercise and provided evidence on information processing speed.[20,44] However, the different duration and intensity employed, as well as the participants' ages, limit the comparability. In an adult study, superior performance was found after a 20 min moderate intensity bout compared to 10 and 45 min durations.[44] In an adolescent study, 30 min of acute high-intensity intermittent physical exercise improved information processing to a greater extent compared to a 60 min bout of comparable intensity.[20] Inconsistencies of the present findings with those of the abovementioned studies might be due to three factors. (a) The exercise duration identified for adults and adolescents might not fit for children, who have lower cognitive and motor developmental and/or skill levels[11] and are therefore more sensitive to exercise-induced effects.[4] (b) The duration of the acute bout is inherently tied and inversely related to the intensity, such that as the intensity of the bout increases, the potential maximum duration decreases.[3] (c) Not physical intensity or cognitive engagement individually, but their interaction determines the overall dose, which may influence the optimal bout duration.[11]

The lack of duration-dependent effects on executive control in the present study adds evidence to previous acute exercise research with children and adolescents, failing to find effects of duration on EFs after a 5–20 min moderate to vigorous classroom-based exercise,[19,21] or after a 10–30 min moderate cycling activity.[22] However, the choice of different combinations of exercise characteristics (intensity, duration, and modality), participants' age, and differences in study design and statistical analyses in the available studies hinder a thorough comparison. Howie and colleagues[21] used separate analyses for the different exercise durations, thus not comparing effects across conditions. Van den Berg et al.[22] compared the effects of different durations in adolescents. Their employed exercise durations, intensities, and cognitive assessment instruments were similar to those used in the current study but without a deliberate inclusion of cognitive challenge. According to the cognitive stimulation hypothesis, cognitively challenging physical exercise that includes cognitive engagement along with physical exertion preactivates similar neural areas associated with EFs, and is therefore thought to have stronger effects on subsequent cognitive performance than a physically demanding exercise with low cognitive engagement.[8] However, the lack of differential duration effects of cognitively challenging bouts of physical exercise on children's EFs does not add further nuances to this hypothesis in regard to exercise duration effects. Instead, our results extend the insensitivity of EFs to acute exercise duration from simply aerobic[22] to also cognitively high-challenging bouts of physical exercise at moderate intensity (with 5 min increments from 5 to 20 min), and from adolescence to childhood. To date, only Graham et al.[19] manipulated the cognitive challenge while investigating the effects of exercise duration on adolescent's EFs. However, unbalanced sampling problems were indicated as a factor that limited the possibility to draw conclusions on the interactive effect of exercise duration and cognitive challenge.

Concerning the second aim of the study, results showed no effects of duration on alerting, orienting, nor on their interaction with the executive control network. This is in line with the lack of differential effects reported in van den Berg et al.'s[22] acute exercise study with adolescents that used the attention network paradigm and investigated the dose–response relation by means of different bout durations of physical exercise (10, 20, or 30 min). However, to the best of our knowledge, neither this,[22] nor other previous exercise studies considered the interaction between attention networks as we did in the present study. Intriguingly, we found evidence of this interaction, which was constrained by the moderating role of children's habitual physical activity level.

Besides the interplay of exercise characteristics, also individual characteristics need to be considered as potential moderators of the effects of bout duration on executive control and other attention networks.[4,7,36,37] The current study included a third exploratory aim to address this issue. Results showed that among environmental, developmental, physical, and cognitive characteristics tested, only habitual physical activity level moderated the effects of duration. Interestingly, habitual physical activity and bout duration jointly affected the interactive performance of the executive control and orienting networks. In general, previous attention network research consistently showed that executive control is worse when spatial attention resources cannot be validly allocated in advance.[14] In our subsample of more active children, this disadvantage in executive control when spatial attentional resources were invalidly allocated was lowest after the 15 min bout of physical exercise. This suggests that children with higher habitual physical activity are better able to capitalize on the cognitive benefits of a 15 min bout of cognitively challenging physical exercise to improve the interactive functioning of their attention networks. In particular, they seem better able to maintain executive control efficiency also when misleading information of invalid spatial cues challenges the orienting network to perform spatial disengagement. This result is consistent with a previous acute cognitively challenging exercise study, suggesting that cognitively challenging bouts of physical exercise benefit only EFs efficiency of children who are physically and cognitively better equipped to capitalize on it.[30] Thus, it seems that only children who are habitually active might be better able to allocate the enhanced attentional resources to the most complex executive task demands (i.e., executive control under disadvantageous spatial conditions), supporting previous evidence on differential effects based on individual characteristics.[4,7,36,37]

In the current study, the four experimental conditions were designed to differ in duration (5, 10, 15, 20 min), but not in cognitive challenge (constantly adapted to the individual ongoing performance) nor in physical intensity (at 65% HR_{max}). Even when the cognitive challenge and physical intensity were held constant, subjective ratings indicated that children perceived the 15 and 20 min conditions as more cognitively and physically demanding than the 5 min condition. However, they did not perceive differences between 5 and 10 min durations and between 15 and 20 min durations. Future research might further investigate duration and intensity thresholds in perceived cognitive engagement and physical exertion during physical exercise.

The exergaming task allowed for individualization and constant modulation of the cognitive challenge based on children's ongoing performance, thus ensuring playing at an optimal challenge point. However, the 20 min condition was perceived as more stressful than the 5 min one, as well as less enjoyable than the two shortest conditions. This result is consistent with a previous acute cognitively challenging physical exercise study with children showing a reduction in positive affect after a 20 min bout at moderate to vigorous intensity.[28] Considering that the effects of acute exercise on positive affect may enhance cognitive performance,[27] future research should manipulate affective responses during cognitively challenging bouts of physical exercise. This may further our understanding of mediators that influence the acute exercise-cognition relation and account for interindividual heterogeneity in response to acute exercise.[1]

4.1 | Limitations

The present study is not without limitations. First, the four durations of acute cognitively challenging physical exercise were completed in a counterbalanced order, but without a sedentary control group. This allowed identifying exercise duration effects (first aim of the study), but hindered disentangling physical exercise and duration related effects. Moreover, due to time constraints posed by schools, we did not include a pre-test assessment for cognition. Future studies should include a sedentary control group and utilize a within-subjects crossover pre- and post-test design. In this design, all participants engage in both the exercise and sedentary control conditions in a counterbalanced order. Thus, individual differences and learning/practice effects can be controlled.[3] Second, according to the cognitive stimulation hypothesis,[8] exercise demands were specifically designed to mirror the attention network paradigm. It remains unclear if, beside near transfer effects of exergaming demands on attention network performances, also far transfer effects on other EFs can be elicited. Future studies should evaluate exercise effects on a variety of more and less distant EF measures to investigate transfer effects, and complement these by multiple levels of analysis (e.g., neuroimaging) to understand the neurobiological mechanisms that drive the changes in behavioral performance.[47] Third, given that a child-adapted version of ANT-R with longer stimulus duration and longer interstimulus interval was used as outcome measure, it is possible that effects were biased toward RTs. As indicated by a recent comprehensive review,[3] selective effects on RTs and accuracy might be due to different task parameters or instructions. Accordingly, tasks with long stimulus duration and long interstimulus interval may bias improvements to manifest within RTs[3] and even small differences in task instruction may lead to large differences in participants' strategies.[48] Future studies are needed to systematically investigate the sensitivity of acute cognitively challenging exercise on children's RTs and accuracy. Therefore, for example, various outcome measures with longer and shorter stimulus durations and interstimulus intervals could be compared.

5 | CONCLUSIONS

The present study produced two main novel findings. Firstly, an acute, 15 min bout of cognitively challenging physical exercise transiently benefited children's information processing speed, with no duration-dependent effects for executive control, alerting and orienting performances and interactions. Secondly, a nuanced pattern of duration-dependent effects on the interactive functioning of executive control and orienting networks emerged for children with higher levels of habitual physical activity. Only for more active children, the 15 min bout of physical exercise enhanced the efficiency of executive control, also when spatial attention resources could not be validly allocated in advance. Taken together, results support a dose–response relation of different durations of acute cognitively challenging physical exercise on basic cognitive processes (e.g., information processing), rather than on more complex executive control and attention processes,[4] and for more active children only, on the interactive functioning of executive control and orienting networks.

6 | PERSPECTIVE

The current results call for more refined study designs tailored to address the interplay between individual characteristics and task characteristics of acute bouts of cognitively challenging physical exercise. Furthermore, they highlight the importance of expanding cognitive outcome measures toward assessment paradigms that allow evaluating exercise effects not only on single cognitive functions but also on the interplay of brain networks that better reflect their intertwined functioning under ecological conditions. Results of such research may be used to design practical activities in ecological settings, as active breaks in the school setting, in which learning outcomes are influenced by the individual and interactive functioning of attention networks.

AUTHOR CONTRIBUTIONS

Conception or design of the work: MS, SA, VB; acquisition of data: SA; data analysis: SA, VB, CZ, JS; interpretation of data for the work: SA, VB, MS; draft of the work: SA, VB, MS, CZ, ALMN. 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.

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CONFLICT OF INTEREST STATEMENT

The authors do not have any conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Sofia Anzeneder https://orcid.org/0000-0003-2839-7567
Cäcilia Zehnder https://orcid.org/0000-0002-7001-2184
Jürg Schmid https://orcid.org/0000-0002-6265-7660
Mirko Schmidt https://orcid.org/0000-0003-4859-6547
Valentin Benzing https://orcid.org/0000-0002-9940-5635

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