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Acute cognitively challenging exercise as “cognitive booster” for children: Positive feedback matters!

Sofia Anzeneder [a,*], Jürg Schmid [a], Cäcilia Zehnder [a], Lairan Koch [a], Anna Lisa Martin-Niedecken [b], Mirko Schmidt [a,1], Valentin Benzing [a,1]

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

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ABSTRACT

Background and aim: Acute exercise can enhance children’s cognition. Heterogeneous effect sizes necessitate investigating exercise task characteristics, contextual factors, and related affective states. The study aimed to test whether different feedback forms during acute cognitively challenging exercise affect children’s executive control, alerting, and orienting performances, also considering the potential mediational role of affective states.
Methods: In a within–subjects posttest only design, 100 children ($M_{\text{age}} = 11.0$, $SD_{\text{age}} = 0.8$, 48% female) participated weekly in one of three exergames with different feedback: no feedback (NO-FB), standard acoustic environment (ST-FB), positive feedback (PO-FB). Acute bouts were designed to keep physical intensity (65% HR_{max}) and duration (15-min) constant and to have a high cognitive challenge. Valence, arousal, perceived physical exertion, cognitive engagement, and flow were assessed before, during and after exergaming. Each bout was followed by an Attention Network Test.
Results: ANOVAs revealed a significant main effect of feedback on executive control ($\eta_p^2 = 0.09$) with faster reaction times after PO-FB compared to the other conditions ($\eta_{ps}^2 > 0.06$) and on valence at post–test ($\eta_p^2 = 0.11$) with highest values in PO-FB ($\eta_{ps}^2 > 0.08$). In PO-FB, valence was associated with executive control ($r = -0.23$) but did not mediate feedback effects on executive control (95% CI [–5.25, 4.68]). Alerting and orienting performances were unaffected by feedback ($\eta_{ps}^2 < 0.08$).
Conclusion: Results suggest that positive feedback during acute cognitively challenging exergaming enhances children’s executive control and positive affect, highlighting that exercise task characteristics and contextual factors are essential for cognitive benefits.

1. Introduction

Physical exercise has a variety of well documented positive effects on mental health both in the long–term after prolonged practice (i.e., chronic exercise) and transiently after a single bout (i.e., acute exercise; Petruzzello et al., 2018). In the cognitive domain, acute exercise effects have been mainly investigated on executive functions (EFs; Pontifex et al., 2019) that encompass a range of processes necessary for regulating thoughts, emotions, and actions relevant to learning and daily functioning (Diamond, 2013).

Within EFs, inhibition is by far the most investigated acute exercise outcome across the lifespan (Pontifex et al., 2019). Research with children especially focused on the executive control component of inhibition, that is the ability to exert control over interference (Diamond, 2013), since it plays a crucial role in behavioral skills relevant to learning, such as self–regulation (Liew, 2012). Interestingly, executive control is not only a component of inhibition (Diamond, 2013), but also one of three independent yet interacting attention networks, along with alerting (i.e., achieving and maintaining an alert state to detect sensory inputs) and orienting (i.e., selecting relevant information from sensory inputs; Fan et al., 2009).

Extensive research with children provides evidence of transient improvements of executive control after acute exercise with small to medium effect sizes (De Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Verburgh et al., 2014). This effect has been attributed to different underlying mechanisms of neurochemical and physiological changes

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[*] Corresponding author. Bremgartenstrasse 145, 3012, Bern, Switzerland.
E-mail address: sofia.anzeneder@unibe.ch (S. Anzeneder).
[1] Mirko Schmidt and Valentin Benzing share senior authorship.

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such as increased blood flow, release of catecholamines, neurotrophins, and glucocorticoid levels (Basso & Suzuki, 2017). In addition, these changes are accompanied by altered physiological states such as increased arousal, facilitating cognitive performance by an increased allocation of attention (i.e., arousal theory; Audiffren et al., 2009).

However, there is still a considerable heterogeneity in effect sizes (Lubans et al., 2022), which raises fundamental questions about the effectiveness of exercise in enhancing EFs (Furley et al., 2023). The observed heterogeneity could be attributed to the fact that cognitive outcomes are (interactively) influenced by exercise task characteristics, individual characteristics, contextual factors, and related affective states. Task characteristics may be qualitative as modality and quantitative as intensity and duration (Lubans et al., 2022; Pesce, 2012). Individual characteristics encompass a range of demographic, biological, developmental, physical, and cognitive factors (Herold et al., 2021; Pesce, 2009). Contextual factors refer to the external and situational conditions of exercise, including the social and physical environment (i.e., where and with whom the exercise is performed), the delivery mode (i.e., the way it is delivered such as face–to–face or virtual reality) and the delivery style of the bout (i.e., the instructional style; Pesce et al., 2023; Vella, Aidman, et al., 2023; Vella, Sutcliffe, et al., 2023). The delivery style encompasses feedback forms grounded on theories such as the macro–theory of positive functioning (Stanley & Schutte, 2023) and evidence–based forms like the use of music (Vella, Aidman, et al., 2023).

A qualitative exercise characteristic that has garnered increasing interest is the cognitive demand (Pesce, 2012), which can be inherent such as in team games or deliberately added/incorporated in less challenging repetitive and automatized movement (Herold et al., 2018). Additional cognitive demands are juxtaposed to the physical task demands, meaning that resolving a cognitive task is not necessary to successfully complete the physical task, and vice versa (e.g., stationary cycling while counting). Incorporated cognitive demands are intertwined with the physical task, meaning that resolving a cognitive task is a prerequisite for successfully completing the physical task, and vice versa (e.g., dancing or delayed imitation tasks; Herold et al., 2018). The cognitive engagement elicited by cognitively challenging exercise seem to pre–activate similar brain regions that are used to control higher–-order cognitive processes leading to better performance in subsequent EF tasks (i.e., cognitive stimulation hypothesis; Budde et al., 2008; Pesce, 2012). This mechanism is further supported by the idea of common neural substrates in both complex cognitive and movement tasks: Combining cognitive and physical demands may elicit synergistic effects due to coactivation and inter–connectedness of prefrontal and cerebellar areas (Becker et al., 2023; Serrien et al., 2007).

However, results of acute cognitively challenging bouts on children's EFs are inconsistent, with findings ranging from negative to positive effects (Paschen et al., 2019). Negative effects on specific facets of EFs (Egger et al., 2018) might emerge when the cognitive engagement required by challenging bouts of exercise exceeds the available cognitive resources, leading to depletion (Audiffren & André, 2015). Schmidt et al. (2021) further elaborated on this, suggesting that a curvilinear function linking the degree of cognitive demand to executive control might be responsible for inconsistent findings of studies that dichotomized lower versus higher cognitive demand. Recently, an experimental study addressed this issue in primary school children by employing three levels of cognitive challenge through a specifically designed exergame (i.e., an active videogame; Anzeneder, Zehnder, Martin–Niedecken, et al., 2023). Results indicated best executive control performance after the high–challenging bout.

Exergaming as a tool to incorporate targeted amounts of cognitive demands into physical exercise has shown promise and is spreading in exercise–cognition research across the lifespan (Benzing & Schmidt, 2018; Stojan & Voelcker–Rehage, 2019). Its major advantages for cognitively challenging acute exercise studies are that (a) experimental conditions can be conducted in a highly standardized and ecologically valid fashion in the field; (b) the manipulation of both physical intensity and cognitive demands of the bout can be finely tuned and adapted online to the individual (Benzing & Schmidt, 2018); (c) the delivery style of exergaming encompasses visual, acoustic and/or tactile feedback forms that provide multiple sources of information (Bernardo et al., 2021). This opens the possibility of investigating the single and combined effects of different exercise task characteristics and contextual factors.

One reason for the inconsistent pattern of results from acute cognitively challenging exercise studies may be that previous studies differed in exercise task and individual characteristics, and largely neglected potential mediators in the affective domain that can be influenced by exercise delivery style (Pesce et al., 2023; Vella, Aidman, et al., 2023). This is surprising, considering that enhanced affective states during exercise may transiently benefit subsequent cognitive performance. Indeed, according to the psychological overcompensation hypothesis of the self–control model, an enhanced affective state during exercise may compensate for the depletion of limited self–regulation resources caused by the exercise task itself (Audiffren & André, 2015). From a neurophysiological perspective, positive affective states generated by exercise may transiently modulate the effectiveness of cognitive processes in the prefrontal cortex involved in EFs and self–regulation (i.e., dopaminergic hypothesis; Audiffren & André, 2015). Moreover, specifically in virtual environments, areas of the right dorsolateral prefrontal cortex activated during affect–regulation efforts seem to reduce their activity when virtual reality cues lessen reliance on cognitive efforts to attenuate unpleasant interoceptive sensations associated with physical exercise effort (Jones & Ekkekakis, 2019).

To effectively enhance affective states, evidence–based delivery styles such as music (Terry et al., 2020) or theory–driven delivery styles such as positive feedback (Fransen et al., 2018) have been proposed. The effectiveness of music is based on synchronization and distraction theories, postulating that music synchronized with movements can increase perceived arousal (Bigliassi et al., 2018) or reduce perceived physical exertion by shifting attention toward external environmental cues (Fritz et al., 2013), respectively. The effectiveness of positive feedback can be explained in the light of the macro–theory of positive functioning that integrates self–determination (Ryan & Deci, 2000) and 'broaden and build' theories (Fredrickson, 2004). According to this macro–theory, higher levels of basic need satisfaction result in enhanced positive affective states, which in turn foster cognition by broadening cognitive processes (Stanley & Schutte, 2023). Specifically, it has been hypothesized that a combination of valence (i.e., activity pleasantness) and arousal (i.e., motivational intensity to approach or avoid certain stimuli) may have an impact on EFs (Kuhbandner & Zehetleitner, 2011).

Although there is consistent evidence supporting positive effects on cognition of chronic exercise with delivery styles in which educators generate engagement and positive affective states (Pesce et al., 2023), the influence of delivery style and related affective states on the relationship between acute cognitively challenging bouts and children's cognitive performance remains largely unexplored. To date, no studies manipulated delivery style characteristics and, to the best of our knowledge, only two studies considered the mediational role of affective states in the relation between acute cognitively challenging exercise and executive control (Bulten et al., 2022; Schmidt et al., 2016). However, findings remain inconclusive with valence mediating the effect of cognitive engagement on executive control in one study (Schmidt et al., 2016), but not in the other (Bulten et al., 2022).

Thus, the first aim of the study was to investigate the effect of different feedback forms (no feedback [NO-FB], standard acoustic environment [ST-FB], standard acoustic environment combined with positive feedback [PO-FB]) during an acute cognitively challenging bout of exergaming on children's (a) executive control (primary outcome); and (b) other attention network performances (i.e., alerting and orienting) and their interactive functioning (Fan et al., 2009). The second aim was to test whether affective states (valence and arousal) also differ between feedback forms. The third aim was to test whether valence and arousal mediate the effect of feedback on cognitive performance. Based on piecemeal evidence of enhanced positive affective states after positive feedback and after exposure to music (Bigliassi et al., 2018; Fransen et al., 2018; Fritz et al., 2013; Peifer et al., 2020), we hypothesized that feedback conditions would differentially impact affective states (PO-FB > ST-FB > NO-FB). Based on the overcompensation hypothesis of the self–control model (Audiffren & André, 2015), according to which cognitive resources are less depleted in presence of positive affective states, we hypothesized that feedback forms would differentially impact cognitive performance, mediated by affective states (PO-FB > ST-FB > NO-FB).

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 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 (BASEC number: 2020–00624), which adhered to the latest Declaration of Helsinki.

2.1. Participants

One hundred eight children aged 10–13 years ($M = 11.0$, $SD = 0.8$; 48% female) were recruited, class–wise, from several primary schools in the region of Bern, Switzerland. To be eligible for the study, children had to be aged between 9 and 13 years old and without a diagnosed developmental disorder affecting cognition or motor function. Moreover, it was mandatory that legal guardians of all children provided written informed consent and that children agreed to participate. For feedback effects on the primary cognitive outcome (i.e., executive control), we conducted an a–priori power analysis using the SuperPower Shiny app. We defined a within–subjects design with three feedback conditions and estimated effects based on a previous acute study (Best, 2012) with alpha error probability = 0.05 and correlation between repeated measures $r = 0.40$. We assumed that children's executive control performance (as difference value, see section 2.5.) would be faster after PO-FB ($M = 100$ ms, $SD = 80$), compared to ST-FB ($M = 110$ ms, $SD = 80$) and NO-FB ($M = 120$ ms, $SD = 80$). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed a power of >80% for Bonferroni–adjusted pairwise comparisons among feedback conditions.

Of the 108 participants recruited, two were excluded due to injuries that occurred outside the study. Due to technical problems with the tablets used for attentional testing, there was some loss of data (1.1%). Since Little's MCAR test has led to a non–significant result ($p = 0.989$), the missing values were imputed using the expectation–maximization algorithm. Participants' background variables are presented in Table 1.

Table 1
Participants' background variables.

Background variables	*M* (*SD*)
Age (years)	11.0 (0.8)
Biological sex (% female)	49%
Socioeconomic status [2–14]	8.9 (2.1)
Body mass index (kg/m^2)	18.6 (3.0)
Pubertal developmental status [3–12]	4.9 (2.0)
Habitual physical activity [1–5]	2.6 (0.6)
VO$_2$max (ml/kg/min)	52.3 (6.6)
Weekly videogame time [min]	39.4 (63.9)
Need for cognition [19–95]	59.5 (10.7)
Need for affect [-30–30]	7.7 (7.5)

2.2. Design and procedures

In the current within–subjects crossover design study, acute bouts consisted in a specifically adapted exergame to ensure standardized manipulation of feedback in one of three conditions: NO-FB, ST-FB, or PO-FB. The study was conducted over a period of four weeks with random counterbalancing of experimental conditions. Specifically, we created six sequences (i.e., all permutations of the three experimental conditions) and randomly assigned each child to one sequence. During the first week, data was collected on two days. On the first day, background characteristics were assessed by a questionnaire including demographic, biological, developmental, physical, and cognitive factors. Subsequently, weight and height were assessed for BMI computation, and children performed the 20–m Shuttle Run test to assess their maximum heart rate (HR) and fitness level. Of this wide range of background variables, the following variables are those derived from the literature, which are commonly controlled for and reported as potentially influencing the acute exercise–cognition relation: Age, biological sex, BMI, socioeconomic status, pubertal developmental status, habitual physical activity (Herold et al., 2021; Ludyga et al., 2016; Pesce, 2009; Pesce et al., 2021). In addition, we assessed variables specifically tailored for the present acute exercise study with cognitively challenging exergaming and manipulation of the affect–inducing feedback form: Weekly videogame practice, need for cognition, and need for affect. Acceptable reliability and validity were demonstrated for background variables (for a detailed description and references see Appendix A). On the second day, children participated in a familiarization session: Each child completed a tutorial of the exergaming intervention that is described below. Subsequently, to familiarize children with attentional testing, they performed the practice block of the revised Attention Network Test (ANT–R; Fan et al., 2009).

Between the second and fourth week, children participated individually in one exergame session per week, which took place at the same time and day each week. Before [pre–test], during (every 5 min), and after exergaming [post–test], valence, arousal, physical exertion, cognitive engagement were collected; flow was assessed during (every 5 min), and after exergaming [post–test]. Variables were assessed in the following order: Valence and arousal, physical exertion, cognitive engagement, and flow. The multiple time points from baseline to post–exergaming allowed to test whether the manipulation was effective, as reflected in the alteration of subjective experiences (e.g., Benzing et al., 2016; Egger et al., 2018). These variables have acceptable reliability and validity (see Appendix A). HR was assessed every 3 s during exergaming to ensure that exercise intensity was kept constant. After each exergaming session, attentional testing was performed with ANT–R (Fan et al., 2009). The experimental protocol and timeline of weekly sessions are depicted in Fig. 1. Each session lasted about 34 min. While children were blinded to conditions, assessors were not.

2.3. Intervention and experimental conditions

Exergaming was used as intervention. It is an enjoyable, physically, and cognitively challenging form of exercise that integrates multimodal immediate feedback systems, ranging from visual animations to music and sound effects (Benzing & Schmidt, 2018; see Appendix B for a detailed explanation of the manipulation of physical and cognitive task demands of exergaming and the following video for exergaming task examples: https://vimeo.com/759054046). During exergaming, participants were immersed in an underwater game scenario and performed different movements (e.g., jumps, squats, punches; Martin–Niedecken et al., 2020). They wore motion–based trackers attached to their wrists and ankles as well as an HR sensor to constantly track their movements and HR. The high cognitive challenge (continuously adapted to the ongoing individual performance across five progressive difficulty levels) and the 15 min bout duration were chosen according to the results of previous studies (Anzeneder, Zehnder, Martin–Niedecken, et al., 2023;

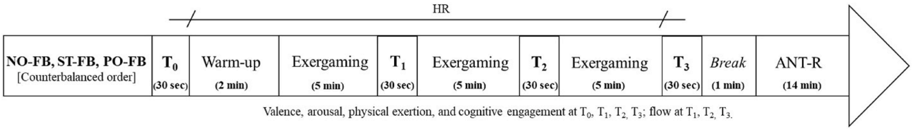


Fig. 1. Experimental protocol of weekly sessions.
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. T_0: Before exergaming, T_1: 5 min exergaming, T_2: 10 min exergaming, T_3: After exergaming. ANT–R: Revised Attention Network Test.

Anzeneder, Zehnder, Schmid, et al., 2023). The physical intensity was maintained at roughly 65% HR_{max} to (a) ensure comparability with most acute exercise–cognition studies (Pontifex et al., 2019); (b) align with evidence of cognitive benefits of moderate to vigorous intensities (Ludyga et al., 2016); and (c) avoid feelings of displeasure typical of vigorous exercise beyond the ventilatory threshold (Benjamin et al., 2012), due to the interplay of cognitive processes and affective responses to different exercise intensities (Ekkekakis, 2008).

Affective states were induced through different feedback forms. During NO-FB, children played the exergame without auditory signals and received only visual feedback integrated into the exergame, indicating the correctness and accuracy of their movements (e.g., stars lighting up for correct movements or gates turning red for incorrect ones), as well as the progression of difficulty levels (i.e., the background of the game scenario was colored differently according to the difficulty level). During ST-FB, visual feedback was accompanied by motivating music that increased in tempo with the difficulty level (i.e., faster tempo during more difficult levels), along with sound effects from the standard version of the exergame (e.g., virtual audience cheering and clapping hands in case of correct movements; see Appendix B). During PO-FB, children played the exergame in ST-FB, and researchers provided 15 standardized positive personal feedback every 5 min of activity. The feedback protocol included phrases such as “well done”, “great”, “very good”, or “keep it up” for correct movements and “no problem”, “go for it”, “you can do this”, or “try again” for incorrect movements.

2.4. Control and manipulation check variables

Several variables were assessed to test whether experimental manipulation had succeeded in eliciting physical exertion and cognitive engagement constantly during the exergaming bout (see Fig. 1). *HR* was assessed with PolarTeam2 belts and transmitters. *Perceived physical exertion* (RPE) and *cognitive engagement* (RCE) were assessed with Borg RPE and the adapted RCE scale, respectively.

Flow was assessed with the Core Flow Scale as a measure of immersion specific to the virtual reality environment. The rationale for including flow as a manipulation check variable was based on evidence that positive feedback enhances flow experience (Peifer et al., 2020), which, in turn, is linked to positive affective states (Huang et al., 2018). Indeed, external visual–auditory cues in a virtual environment may lessen reliance on cognitive effort to attenuate unpleasant interoceptive sensations associated with effortful exercise (Jones & Ekkekakis, 2019). Acceptable psychometric properties have been shown for all control and manipulation check variables (see Appendix A).

2.5. Cognitive performance

A child–adapted version of ANT–R (Fan et al., 2009) was used on Inquisit 5 to assess the efficiency of: (a) *executive control* (primary outcome), (b) *alerting* and *orienting performances*, as well as (c) the *interaction of executive control with alerting and orienting networks*. For the primary outcome, a retest reliability ranging from 0.61 to 0.71 has been shown (Macleod et al., 2010); it largely overlaps with that computed on the present dataset (ICC: 0.70 to 0.85). There are four cue conditions (no, double, valid spatial, invalid spatial) and two congruency conditions (central target arrow surrounded by congruent or incongruent flanker arrows). Children must identify the direction of the center arrow by pressing a right or left button while ignoring flanker arrows. Reaction times (RTs) and response accuracy are recorded. Each attention system performance is computed as a difference value of RTs and accuracy. For example, executive control (flanker effect) is calculated as [incongruent – congruent trials]. See Appendix C for a detailed description of ANT–R.

2.6. Affective states

Valence was assessed using the *Feeling Scale* (FS; Hardy & Rejeski, 1989). Children were asked to rate their present feelings on an 11–point bipolar single–item scale that ranges from −5 (very bad) to +5 (very good) along a displeasure–pleasure continuum. *Arousal* was assessed using the single–item pictorial Self–Assessment Manikin (SAM; Bradley & Lang, 1994). For both scales, acceptable psychometric properties have been provided with a convergent validity of $r = 0.67$ for valence (between FS and SAM valence subscales) and $r = 0.31$ for arousal (between SAM arousal subscale and Felt Arousal scale; Thorenz et al., 2024). In the present dataset, reliability was good for valence (ICC: 0.74 to 0.87) and acceptable for arousal (ICC: 0.65 to 0.82).

2.7. Statistical analyses

Analyses were performed using IBM SPSS version 27.0. Preliminary analyses were run using repeated measures ANOVAs for the comparison of control and manipulation check variables among feedback conditions over exergaming time. A further ANOVA was run to compare HR average among feedback conditions. An initial 3 (feedback conditions) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVA model was performed, separately for overall RTs and response accuracy, to test whether the classical cue–and flanker effects reported in the literature (Fan et al., 2009) could be replicated and were affected by feedback conditions.

For main analyses of the primary outcome, a repeated measures ANOVA model with feedback condition as factor was run separately for RT and accuracy differences, computed by subtracting flanker conditions pairwise in a theory–driven manner (see Appendix C). Subsequently, these difference values were used to contrast feedback effects using post–hoc Bonferroni–adjusted pairwise comparisons. For alerting and orienting performances and their interactions with executive control, analogous repeated measures ANOVA models were run separately for RT and accuracy differences, computed by subtracting cue conditions pairwise in a theory–driven manner (see Appendix C), followed by post–hoc Bonferroni–adjusted pairwise comparisons.

To test the effects of feedback on affective states over exergaming time and differences in affect at the different time points, a 3 (feedback conditions) × 4 (time points) repeated measures ANOVA model was performed separately for valence and arousal. Bonferroni–adjusted post–hoc pairwise comparisons were used to evaluate feedback × time effects. Subsequently, to test the effect of feedback on affective states, a repeated measures ANOVA model was performed with feedback as factor and, separately, with valence and arousal at post–test. We used post–test scores of affective states to ensure that intervention effects on mediating variables (affective states) and outcomes (cognitive performance) emerge from the same experimental design. However, we also satisfied temporal ordering assumptions (Stuart et al., 2021) by assessing post–exercise affective states before cognitive performance, necessarily separated by less than 2 min in an acute study designed to assesses short–term, transient effects.

In case of significant feedback effects of the main ANOVAs on cognitive performance, bivariate correlations were calculated to test the association of the cognitive performance of interest with post–test scores of affective states. Subsequently, bias–corrected bootstrap analyses (95% BC confidence interval) were calculated using SPSS MEMORE syntax to test potential mediations and reveal the indirect effects as significantly different from zero (Montoya & Hayes, 2017). In this multiple mediation model the independent variables were the pairwise contrasted feedback conditions that were found to be significant in the previous analyses. The mediating variables were post–test scores of valence and arousal. The dependent variables were cognitive performances that were significantly influenced by feedback. For each significant pairwise feedback comparison, we calculated difference values that reflect the mean tendency in the groups (Montoya & Hayes, 2017).

In an additional exploratory analysis, the potential influence of individual–level covariates was investigated using the same 3 × 4 × 2 repeated measures analysis model in a subsequent ANCOVA, including background variables as covariates (age, biological sex, BMI, pubertal developmental status, socioeconomic status, habitual physical activity, cardiovascular fitness, need for cognition, need for affect, weekly videogame practice). For all analyses, median RTs were used because of the non–normal distribution of RTs. All analyses were performed also on mean RTs, with and without the six multivariate outliers identified through Mahalanobis distance ($p < 0.001$); results show a similar pattern of effects. The significance level was set at $\alpha = 0.05$ for all analyses and η_p^2 was reported as effect size estimation (small effect size = 0.01, medium effect size = 0.06, large effect size = 0.14).

3. Results

3.1. Control and manipulation check variables

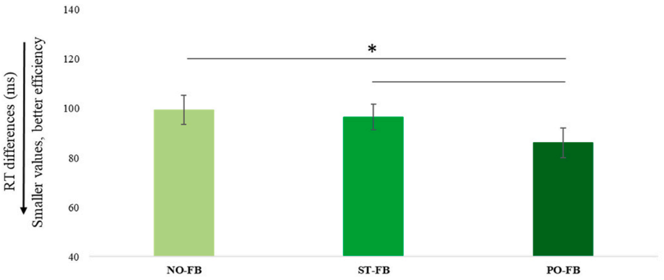
Descriptive statistics of control and manipulation check variables among time points are presented in Appendix D. For RPE and RCE a significant effect of time emerged (RPE: $p < 0.001$; $\eta_p^2 = 0.79$; RCE: $p < 0.001$; $\eta_p^2 = 0.68$). The intended similarity among conditions was also confirmed by objective HR data ($p = 0.164$, $\eta_p^2 = 0.04$). Concerning flow, significant effects of time ($p < 0.001$; $\eta_p^2 = 0.35$) and feedback condition emerged ($p < 0.001$; $\eta_p^2 = 0.29$). As concerns feedback effects of interest, flow experience was higher in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p < 0.001$, $\eta_p^2 = 0.21$; PO-FB vs. ST-FB: $p < 0.001$, $\eta_p^2 = 0.22$) with no further differences (ST-FB vs. NO-FB: $p = 0.257$, $\eta_p^2 = 0.03$).

3.2. Cognitive performance

A first ANOVA on overall RTs replicated the cue– (F [3, 97] = 357.23, $p < 0.001$, $\eta_p^2 = 0.92$), flanker– (F [1, 99] = 393.55, $p < 0.001$, $\eta_p^2 = 0.79$) and cue × flanker effects (F [3, 97] = 10.00, $p < 0.001$, $\eta_p^2 = 0.24$) reported in the literature (Fan et al., 2009).

Regarding main analyses of the primary outcome, a significant feedback condition effect on executive control RTs with medium effect size emerged (F [2, 98] = 4.58, $p = 0.013$, $\eta_p^2 = 0.09$; see Fig. 2). Post–hoc pairwise comparisons revealed faster RTs after PO-FB compared to NO-FB ($p = 0.023$, $\eta_p^2 = 0.07$) and ST-FB conditions ($p = 0.033$, $\eta_p^2 = 0.06$), whereas NO-FB and ST-FB did not differ from each other ($p = 1.000$, $\eta_p^2 = 0.04$). There were no feedback effects for accuracy ($p = 0.917$, $\eta_p^2 < 0.01$), indicating a lack of speed–accuracy trade–off effects.

No feedback effects emerged for RT and accuracy performances under cue conditions that reflect the efficiency of alerting or orienting networks (*RT*: $p = 0.206$, $\eta_p^2 = 0.08$; *accuracy*: $p = 0.716$, $\eta_p^2 = 0.04$). No effects of feedback emerged for the interaction of executive control with alerting and orienting (*RT*: $p = 0.778$, $\eta_p^2 = 0.03$; *accuracy*: $p = 0.124$, $\eta_p^2 = 0.09$). Further ANCOVAs revealed no significant interaction effects of feedback with individual characteristic ($ps > 0.05$, $\eta_{ps}^2 < 0.09$).



Flanker effect	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
	99.47 (5.86)	96.55 (5.23)	86.18 (6.02)

Fig. 2. Feedback effects on executive control (flanker effect).
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Flanker effect is computed as RT difference [incongruent – congruent trials]. Error bars represent the standard error of the mean. *Significant differences: PO-FB vs. NO-FB: $p = 0.023$, $\eta_p^2 = 0.07$; PO-FB vs. ST-FB: $p = 0.033$, $\eta_p^2 = 0.06$.

3.3. Affective states

A significant effect of time emerged for valence ($p < 0.001$, $\eta_p^2 = 0.24$) and arousal ($p < 0.001$, $\eta_p^2 = 0.61$). For valence only, a significant effect of feedback condition emerged ($p = 0.010$; $\eta_p^2 = 0.09$) with higher scores in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p = 0.011$, $\eta_p^2 = 0.08$; PO-FB vs. ST-FB: $p = 0.042$, $\eta_p^2 = 0.04$). For arousal only, a significant effect of time × feedback condition emerged ($p = 0.009$; $\eta_p^2 = 0.16$) with higher values in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p = 0.046$, $\eta_p^2 = 0.04$; PO-FB vs. ST-FB: $p = 0.047$, $\eta_p^2 = 0.04$). See Appendix D for a detailed description feedback condition and time × feedback condition effects on valence and arousal.

Moreover, a significant effect of feedback emerged on post–test scores of valence (F [2, 98] = 5.92, $p = 0.004$, $\eta_p^2 = 0.11$), but not arousal ($p = 0.425$, $\eta_p^2 = 0.02$; see Fig. 3). Pairwise comparisons showed that PO-FB was perceived as most pleasant (PO-FB vs. NO-FB: $p = 0.003$, $\eta_p^2 = 0.09$; PO-FB vs. ST-FB: $p = 0.004$, $\eta_p^2 = 0.08$) with no differences between ST-FB and NO-FB ($p = 0.538$, $\eta_p^2 = 0.00$; see Fig. 3)

3.4. Affective states and cognitive performance: correlations and mediations[22]

To investigate whether beneficial effects on executive control found after PO-FB were associated with affective states after PO-FB, executive control RTs (flanker effect) as well as RTs under incongruent and congruent flanker conditions were submitted to bivariate correlation with post–test scores of valence and arousal. Valence correlated with executive control RTs (flanker effect) as well as with RTs under both incongruent and congruent conditions. Arousal showed no significant correlations (see Table 2).

In addition, post–test scores of valence and arousal did not mediate feedback effects on executive control performance (see Fig. 4), and valence and arousal did not account for a different proportion of

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[2] Due to the exploratory nature of mediation analyses (Bulten et al., 2022; Schmidt et al., 2016) and considering evidence of potential affective rebounding effects after cessation of exercise (Ekkekakis et al., 2011), correlations and mediations were also run with affective states' change scores (Post–Pre/Pre). Analyses show similar results: (a) valence only was associated with executive control RTs in PO-FB ($r = -0.21$, $p = 0.033$); (b) neither valence (PO-FB vs. NO-FB: 95% CI [–2.61, 6.46]; PO-FB vs. ST-FB: 95% CI [–0.41, 4.28]) nor arousal (PO-FB vs. NO-FB: 95% CI [–2.37, 4.16]; PO-FB vs. ST-FB: 95% CI [–2.78, 1.63]) mediated feedback effects on executive control.

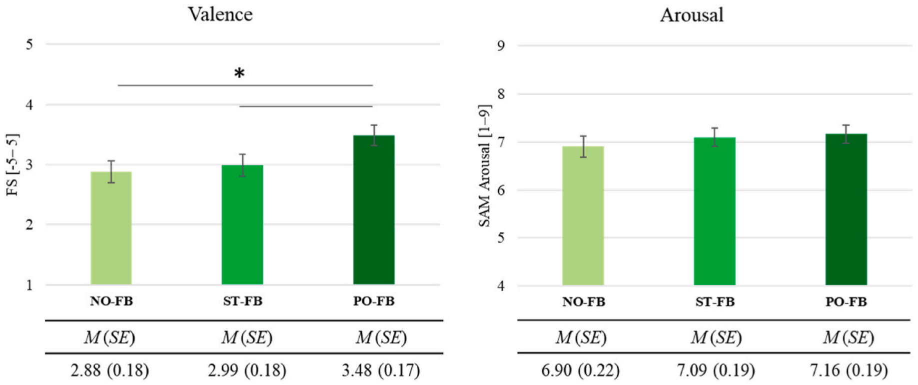

Fig. 3. Feedback effects on post–test scores of affective states.
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Error bars represent the standard error of the mean. *Significant differences: PO-FB vs. NO-FB: $p = 0.003$, $\eta_p^2 = 0.09$; PO-FB vs. ST-FB: $p = 0.004$, $\eta_p^2 = 0.08$.

Table 2
Correlation coefficients among executive control performance and post–test scores of affective states in each feedback condition.

Affective states	Executive control RTs	RTs incongruent	RTs congruent
PO-FB:			
Valence	**$r = -0.23$, $p =$ 0.029**	**$r = -0.20$, $p =$ 0.042**	**$r = -0.26$, $p =$ 0.008**
Arousal	$r = -0.05$, $p =$ 0.655	$r = -0.14$, $p =$ 0.155	$r = -0.14$, $p =$ 0.165
ST-FB:			
Valence	$r = -0.04$, $p =$ 0.684	$r = -0.02$, $p =$ 0.813	$r = -0.01$, $p =$ 0.915
Arousal	$r = -0.09$, $p =$ 0.403	$r = -0.17$, $p =$ 0.100	$r = -0.17$, $p =$ 0.084
NO-FB:			
Valence	$r = -0.03$, $p =$ 0.748	$r = -0.01$, $p =$ 0.949	$r = 0.01$, $p = 0.939$
Arousal	$r = -0.05$, $p =$ 0.650	$r = -0.05$, $p =$ 0.629	$r = -0.04$, $p =$ 0.697

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. RTs: Reaction times. Executive control is calculated as [incongruent – congruent trials]. Significant results bolded.

variance (see Table 3).

4. Discussion

The present study aimed to extend to acute exercise–cognition research a novel interest in the role of contextual factors that recently emerged in the field of chronic exercise studies in relation to cognitive (Pesce et al., 2023) and, more broadly, mental health outcomes (Vella, Aidman, et al., 2023; Vella, Sutcliffe, et al., 2023). Within the broader construct of contextual factors, we focused on the delivery style as a key aspect influencing affective states (Pesce et al., 2023). Specifically, we evaluated the effect of different feedback forms during an acute cognitively challenging exergaming on children's cognitive performance. Moreover, we examined whether feedback forms influence affective states, and whether affective states induced by the exercise bout mediate feedback effects on cognitive performance. Results suggest that positive feedback benefited children's executive control and enhanced affective states most. Conversely, the efficiency of alerting, orienting, and their interaction with executive control was unaffected by feedback forms. Among affective states, only valence elicited by positive feedback was associated with the subsequent executive control performance; however, neither valence nor arousal mediated feedback effects on executive control.

As concerns the first research aim (i.e., feedback effects on cognitive performance), results suggest that delivery styles such as positive feedback matter: In line with our hypothesis, executive control seems to benefit most when children receive positive feedback. Given that under this feedback condition, children were faster in conflict resolution while maintaining a high response accuracy, these effects were likely not due to a speed–accuracy trade–off. However, feedback forms seem not to

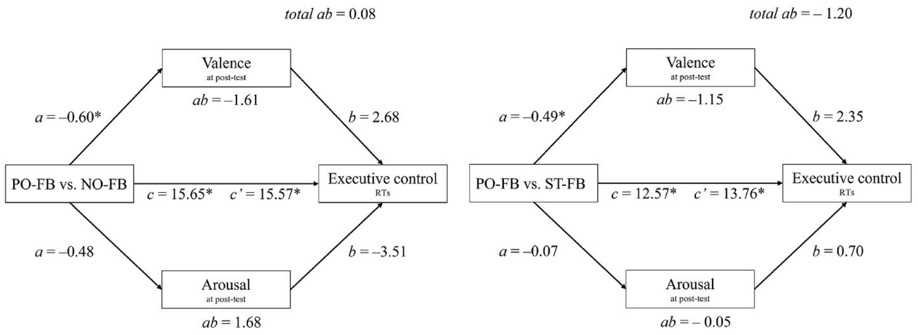

Fig. 4. Mediation model with feedback comparisons as predictors, affective states as mediators, and executive control RTs as outcome variable
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. RTs: Reaction times. Paths a, b, c, and c': Estimates of fixed effects. Path ab: Indirect effect.
*$p < 0.05$.

Table 3
Mediation model with feedback comparisons as predictors, affective states as mediators, and executive control RTs as outcome variable (point estimates, standard errors, and 95% bias-corrected bootstrap confidence intervals).

Path	*M*	*SE*	*(LLCI, ULCI)*
Panel A. PO-FB vs. NO-FB			
Path c	15.65[a]	5.75	4.24, 27.05
Path c'	15.57[a]	6.14	3.37, 27.77
Path a (valence)	−0.60[a]	0.19	−0.99, −0.21
Path a (arousal)	−0.48	0.21	−0.89, −0.07
Path b (valence)	2.68	3.21	−3.70, 9.06
Path b (arousal)	−3.51	3.01	−9.49, 2.47
Path ab (valence)	−1.61	1.92	−6.08, 1.72
Path ab (arousal)	1.68	1.91	−1.37, 6.09
Pairwise contrasts between indirect effects of valence and arousal	−3.29	2.92	−9.99, 1.57
Path ab total	0.08	2.47	−5.25, 4.68
Panel B. PO-FB vs. ST-FB			
Path c	12.57[a]	4.84	2.95, 22.18
Path c'	13.76[a]	5.10	3.64, 23.89
Path a (valence)	−0.49[a]	0.17	−0.82, −0.16
Path a (arousal)	−0.07	0.14	−0.36, 0.22
Path b (valence)	2.35	3.06	−3.73, 8.42
Path b (arousal)	0.70	3.46	−6.17, 7.58
Path ab (valence)	−1.15	1.35	−4.07, 1.39
Path ab (arousal)	−0.05	0.47	−1.15, 0.83
Pairwise contrasts between indirect effects of valence and arousal	−1.10	1.48	−4.26, 1.79
Path ab total	−1.20	1.37	−4.02, 1.32

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Paths a, b, and c': Estimates of fixed effects. Path ab: indirect effect.

[a] $p < 0.05$.

differentially influence children's alerting, orienting, or their interaction with executive control. Speculatively, the fact that only executive control but not the other attention networks were susceptible to acute exergame–based bouts might be interpreted according to evidence of selectively larger exercise effects on tasks that require greater inhibitory control, as in the case of incongruent task conditions (Lubans et al., 2022). The absence of effects on alerting and orienting performances is in line with available evidence that neither a routine aerobic exercise (van den Berg et al., 2018) nor a cognitively challenging exergaming (Anzeneder, Zehnder, Martin–Niedecken, et al., 2023; Anzeneder, Zehnder, Schmid, et al., 2023) seems to influence these networks and might depend on ANT–R indices reliability: The higher within–subject variance found for alerting and orienting compared to executive control indices suggests that in the context of within–subjects designs, the first probably have lower statistical power than the latter (MacLeod et al., 2010). Moreover, feedback effects on cognitive performance were not moderated by any individual characteristic; future studies powered to consider this wide range of covariates are needed to confirm the generalizability of results to preadolescent children, independently of interindividual differences in biological, developmental, physical, and cognitive factors.

As concerns the second aim (i.e., feedback effects on affective states), results suggest that positive feedback provided from researchers during exergaming enhances valence more than the sole immersion in the exergame with or without music. A possible explanation for the personal feedback effects is that encouraging, supportive feedback provided by researchers fulfills basic psychological needs (Ryan & Deci, 2000) and reinforces children's perceived competence, thus enhancing affective states (Fransen et al., 2018). This supposition is confirmed by the flow experience being higher in the positive feedback compared to the other conditions. In fact, positive feedback may enhance the likelihood of flow because it reinforces individuals' feeling of confidence in task completion (Peifer et al., 2020). Speculatively, in the absence of direct measures of neurophysiological indices, this explanation aligns with evidence that both immersion and flow experiences in a virtual reality environment are reflected in a reduced activation of areas of the prefrontal cortex. Virtual reality cues may shift the attentional focus away from internal body signals and reduce cognitive control over the affective responses to them, as reflected in the reduced activation in the right dorsolateral prefrontal cortex (Jones & Ekkekakis, 2019). In addition, positive feedback that enhances flow experience may reduce self–referential processing, as reflected in a decreased activation of the medial prefrontal cortex (Ulrich et al., 2014).

The absence of differential effects between only visual and visual–acoustic feedback conditions (i.e., no feedback and standard acoustic environment, respectively) on affective states was unexpected, as it didn't support synchronization and distraction theories (Bigliassi et al., 2018; Fritz et al., 2013). In fact, children perceived the standard acoustic environment as equally flow–eliciting as the no feedback form. A possible explanation refers to the unique exergaming environment. This environment, rich in visual animation and immersive elements (Martin–Niedecken et al., 2020), has been shown to induce positive affective responses by shifting attention from interoceptive to visual–acoustic exteroceptive stimuli (Jones & Ekkekakis, 2019). This immersion may have captured children's attention to a point that adding music and sound effects as in the standard acoustic environment condition was not effective in further enhancing the experience of presence (Cummings & Bailenson, 2016).

More interestingly, beyond the individual effects of feedback on cognitive performance and affective states, the third aim was to investigate whether affective states explain the effect of feedback on cognitive performance. Our study provides suggestive evidence that after positive feedback valence is weakly associated with executive control performance, but it does not mediate feedback effects on executive control. The association between valence and executive control partially aligns with the overcompensation hypothesis of the self–control model and the dopaminergic hypothesis (Audiffren & André, 2015), according to which, positive feedback may have generated an optimal affective state to improve EFs. However, the absence of a mediation of valence and arousal does not support the hypothesis that an affective mechanism may underlie the transient benefits on executive control of a cognitively challenging exergaming coupled with positive feedback. Since exergaming is highly motivating and immersive, future studies may want to contrast the mediating role of valence and arousal in bouts of exercise with a different delivery mode (e.g., face-to-face).

The potential of exercise to boost EF performance while inducing positive affect has been highlighted in recent evidence synthesis of chronic exercise studies (Pesce et al., 2023), suggesting that delivery styles that challenge EFs, while also eliciting emotional investment, may maximize exercise benefits on cognition. However, in acute exercise and cognition research with children, most studies did not consider affective states at all (e.g., Budde et al., 2008; Egger et al., 2018; Flynn & Richert, 2018), merely used them as potential covariates (e.g., Anzeneder, Zehnder, Martin–Niedecken, et al., 2023; Anzeneder, Zehnder, Schmid, et al., 2023; Bedard et al., 2021; Benzing et al., 2016), or tested a potential mediation of valence only but led to inconsistent conclusions (Bulten et al., 2022; Schmidt et al., 2016). Schmidt et al. (2016) found evidence for mediation, whereas Bulten et al. (2022) did not, suggesting that the absence of mediation might be due to a ceiling effect in affective responses to the experimental manipulation. Our study, instead, did not exhibit this limitation, since manipulation check variables, along with affective states and the executive control performance of interest, seemed to be differentially sensitive to the positive feedback condition compared to the other feedback forms. Nevertheless, our results cannot support the notion that affective states are psychological mechanisms underlying the transient effect of a cognitively challenging bout of exercise on children's executive control. Thus, our lack of mediation does not support the assumptions of the macro–theory of positive functioning, suggesting that delivery styles that encourage competence can effectively enhance affective states that, in turn, broaden cognitive functioning, leading to more efficient conflict resolution (Stanley & Schutte, 2023). Moreover, the fact that valence and arousal did not account for a different proportion of variance misaligns with previous evidence of independent effects of these affective states on executive control (Kuhbandner & Zehetleitner, 2011). Future research should increasingly consider the interplay between valence and arousal and disentangle their impact on cognitive performance.

This study has limitations that should be noted. First, the choice of the study design was influenced by the need to set priorities between main manipulations to address the first study aim and time availability in the ecological school setting. Since the first aim of the study was not to examine acute exergame effects on executive control, but rather to identify the effect of different feedback forms on it, we did not include a sedentary control group or a pre–test assessment of cognitive performance. Thus, we could neither disentangle exercise and feedback effects, nor exclude the influence of day–to–day variability on cognitive performance. However, to minimize the influence of day–to–day variability, we rigorously matched all testing conditions across participants and scheduled exergaming sessions and attentional testing always at the same day and time for each child. Future studies should additionally include a sedentary control group and incorporate a within–subjects, crossover pre–posttest comparison (Pontifex et al., 2019) to allow to control, in mediation analyses, for mediator–outcome confounders such as baseline performances (Stuart et al., 2021; Vo et al., 2020). Second, we did not include a fourth experimental condition of feedback provided by an avatar integrated into the exergame that would have allowed to disentangle the added positive value of the personal, human factor from the positive feedback content, which remains an issue for future research. Third, the absence of physiological and neuroimaging measures of affective states and of cognitive processes constrains the proposed interpretations in terms of underlying mechanisms that combine neuroscience and psychological perspectives (Chang, 2016; Wilson et al., 2020). Fourth, to better understand the nuanced pattern of feedback effects on children's cognition, further research should include additional measures of individual characteristics, such as perceived competence, which might have been influenced by feedback (Fransen et al., 2018) and could potentially account for the observed feedback effects on cognition. Lastly, our sample size was powered for the main analyses on the primary outcome; the additional exploratory analysis considering background characteristics as covariates may have been underpowered to detect their influence and ensure generalizability to children differing in those characteristics.

5. Conclusions and practical implications

Results suggest that combining cognitively challenging exergaming with supportive, encouraging feedback benefit children's executive control more than exergaming without positive feedback. The mechanisms driving such effects likely go beyond the mere enhancement of affective states. Speculatively, it might be that positive feedback and encouragement, combined with the provision of individually adapted cognitive and physical challenges, also supported children's perceived competence (Fransen et al., 2018).

Some characteristics of exergaming, such as the feeling of immersion, the simultaneous integration of physical and cognitive challenges, and positive feedback that have been proven efficacious in the present study might also be transferred into traditional physical activity or sport games without virtual reality. The feeling of immersion, unique to virtual reality, may also be generated to some extent in educational settings for young children by coupling storytelling and physical activity, whose additive effects have been investigated in chronic physical activity research (Duncan et al., 2019; Mavilidi et al., 2023). For school children, both in physical education and during active breaks in the classroom, traditional physical activity games may be altered to generate a progression of complexity similar to that of exergaming, while eliciting imaginative immersion in different environments (e.g., traditional games adapted to imaginative environments as sky and undersea with incremental demands on inhibition; Tomporowski et al., 2015). The outcomes of this study might also inform the development and refinement of cognitive demands to be embedded into enriched sports activity programs (e.g., Alesi et al., 2020). Lastly, since positive feedback during exergaming resulted in cognitive benefits and affective enhancement, the above manipulations of exercise task complexity in educational and sports contexts could be coupled with positive feedback which, beyond its motivating role (Fransen et al., 2018; Mouratidis et al., 2008), may allow to reap largest cognitive benefits. In conclusion, the results of the study, though obtained through the specific delivery mode of exergaming, provide evidence that contributes to embedding the acute exercise–cognition relation into a broader framework of research and application that encompasses cognitive and affective dimensions of exercise task characteristics and contextual factors.

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Ethical approval

Ethical approval was granted by the respective cantonal ethics committees (BASEC 2020-00624) and the trial was registered at ClinicalTrials.gov (DRKS00023254).

CRediT authorship contribution statement

Sofia Anzeneder: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jürg Schmid:** Writing – review & editing, Methodology. **Cäcilia Zehnder:** Writing – review & editing, Methodology. **Lairan Koch:** Writing – review & editing, Data curation. **Anna Lisa Martin-Niedecken:** Writing – review & editing, Conceptualization. **Mirko Schmidt:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Valentin Benzing:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mhpa.2024.100621.

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