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Together towards better executive functions? Effects of acute cognitively demanding physical activity and social interaction on inhibition

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ABSTRACT

Background and aims: Research has shown that acute physical activity (PA) improves inhibition performance. However, further information is needed on potential moderators that may influence this effect. Since social interaction (SoI) was proposed as an important PA characteristic influencing the PA-inhibition relation, this study examines the effects of acute PA and SoI on inhibition.

Methods: In a 2 × 2 within-subject design, 96 participants (17–26 years, M = 20.5; SD = 1.7, 50% female) underwent four experimental conditions, consisting of a cognitively challenging (exer-)game varying in PA (PA/no PA) and SoI (SoI/no SoI). After each condition, inhibition performance was assessed using the Eriksen Flanker Task.

Results: Repeated measures ANOVAs revealed that acute PA enhanced inhibition, leading to faster reaction times ($\eta^2_p = 0.169$) and higher accuracy rates ($\eta^2_p = 0.090$). However, the results showed speed-accuracy trade-offs for SoI, with faster reaction times ($\eta^2_p = 0.041$) and lower accuracy rates ($\eta^2_p = 0.140$). No interaction effects for PA and SoI on inhibition were observed ($\eta^2_{ps} = 0.005$–0.036).

Conclusion: Our findings confirm that an acute bout of cognitively challenging PA can enhance inhibition performance but has no joint effects with SoI, which facilitated performance speed but worsened accuracy. Likely, the physically and cognitively challenging nature of the exergaming bout may have limited room for further improvement by SoI. Future acute PA studies should jointly explore the role of SoI and cognitive engagement in acute PA to identify an optimal pattern of task and context factors for reaping executive functions (EFs) gains.

1. Introduction

The beneficial effects of acute physical activity (PA) contribute not only to better physical health but also to enhanced cognitive functioning, as demonstrated especially for frontal-dependent cognition, such as executive functions (EFs; Erickson et al., 2019; Pontifex et al., 2019). Accumulating evidence highlights the importance of EFs in terms of mental and physical health, quality of life, school and job success, and prevention of social problems (Cristofori et al., 2019).

EFs refer to top-down processes that control and organize goal-directed behavior (Zelazo & Carlson, 2012). Based on the model by Miyake et al. (2000) and a large-scale re-analysis of latent variable studies (Karr et al., 2018), there seem to be three core EFs, namely inhibition, working memory, and cognitive flexibility. Inhibition is the ability to suppress dominant, autonomic, and prepotent responses and thoughts and exert control over interference. Working memory involves the active monitoring and updating of information held in mind. Cognitive flexibility refers to the ability to shift between mental sets (Miyake et al., 2000).

Systematic reviews show that acute PA transiently improves EFs, with most studies investigating inhibition (e.g., Pontifex et al., 2019). Meta-analytic results show moderate effects of PA on inhibition but no significant effects on cognitive flexibility or working memory (Haverkamp et al., 2020). The majority of studies focused on quantitative characteristics of PA (intensity, duration) and examined their dose-response relationships with cognitive outcomes (Chang, Labban, Gapin, & Etnier, 2012; Lubans, Leathy, Mavilidi, & Valkenborghs, 2021; Pontifex et al., 2019). Results show that a duration of 11–20 min of

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moderate-intensity PA (64–76% of maximal heart rate [HRmax]) is most effective for enhancing inhibition (Chang et al., 2012, 2015). However, there is high heterogeneity in effect sizes across studies (Lubans et al., 2021). Beyond the quantitative PA characteristics (e.g., intensity, duration), recent theoretical models stress the influence of other potential moderators that are more qualitative in nature (e.g., PA type or modality, mental resources allocated to, and positive affect elicited by PA; e.g., Pesce, 2012; Pesce et al., 2023). In particular, cognitive engagement in PA has been proposed to influence cognitive performance individually and in combination with quantitative PA characteristics (Pesce, 2012; Tomporowski & Pesce, 2019).

Cognitive engagement refers to allocating effort and attentional resources to manage a challenging situation (Tomporowski, McCullick, Pendleton, & Pesce, 2015). As PAs vary in complexity, different levels of cognitive engagement and skills are necessary, which depend on EFs for successful task execution (e.g., Pesce, 2012; Pesce, Ballester, & Benzing, 2021; Tomporowski & Pesce, 2019). Team sports, for example, frequently demand quick adaptation to dynamic situations, strategic decision-making, inhibition of non-productive thoughts, and the memorization of opponents' playing habits to develop effective tactics (Heilmann, Weinberg, & Wollny, 2022). These open-skill sport activities may elicit higher cognitive engagement levels than closed-skill activities, with repetitive movement patterns in predictable environments, such as running on a treadmill (Pesce et al., 2021).

According to the cognitive stimulation hypothesis, the level of cognitive engagement is decisive for benefiting EFs. This hypothesis assumes that non-routine, cognitively demanding PAs stimulate frontal-dependent, higher-order cognitive processes, particularly EFs (Best, 2010; Diamond & Lee, 2011), leading to a larger enhancement of EFs than lower cognitively demanding PAs that persist after activity cessation (e.g., Pesce, 2012). Empirical evidence supports the cognitive stimulation hypothesis (Benzing, Heinks, Eggenberger, & Schmidt, 2016; Schmidt, Benzing, & Kamer, 2016). In addition, studies systematically analyzing the level of cognitive challenge and the duration of PA bouts found that a 15-min session of moderate PA, coupled with a high cognitive challenge, is most effective for enhancing EFs (Anzeneder, Zehnder, Martin-Niedecken, Schmidt, & Benzing, 2023; Anzeneder, Zehnder, Schmid, et al., 2023).

However, these experimental studies systematically investigated PA characteristics in an individual setting, whereas, from an ecological perspective, PAs are frequently performed in a social setting. PA in a social setting creates opportunities for various forms of social interaction (SoI), including competing with others (Liepelt & Raab, 2021), conveying mutual interests, enjoying friendship (Darker, Larkin, & French, 2007), exchanging task-relevant information (Le Couteur & Feo, 2011), or collaborating towards shared goals (Mcewan & Beauchamp, 2014).

SoI refers to a reciprocal process where one partner's action affects the others, thus representing the participatory aspects of social understanding (De Jaegher, Di Paolo, & Gallagher, 2010; Redcay & Schilbach, 2019). SoI manifests in various forms, such as competitive/collaborative, formal/informal, and affiliative/transactional (Hadley, Naylor, & Hamilton, 2022). It can encompass both verbal and nonverbal communication (De Jaegher et al., 2010) and is determined by the situation, the number of actors involved, and their engagement, status, relationship, and purposes (Hadley et al., 2022).

To participate successfully in SoIs, individuals need abilities such as understanding and interpreting their own and others' mental states (Krach, Paulus, Bodden, & Kircher, 2010), adapting flexibly to changing environmental demands (Maliske, Schurz, & Kanske, 2023), controlling emotions (Schmeichel & Tang, 2015), communicating effectively, and adhering to social norms (Perry et al., 2019). Thus, complex social behaviors, such as SoI, rely on EFs (Cristofori, Cohen-Zimerman, & Grafman, 2019).

The relation between EFs and SoI is bidirectional: EFs play a crucial role in supporting SoI, and SoIs contribute to the development of EFs (Moriguchi, 2014). In recent decades, increasing theoretical work has been devoted to understanding this complex bidirectional relationship (e.g., Lewis & Carpendale, 2009; Moriguchi, 2014; Schulte, Trujillo, Villagra, Salas, & Ibañez, 2022; Ybarra & Winkielman, 2012). EFs and social processes, such as SoI, are functionally connected (Perry et al., 2019), with a neuroanatomical overlap of brain regions associated with cognitive and social processes (Lanooij, Eisel, Drinkenburg, van der Zee, & Kas, 2022). Notably, a systematic review that addressed brain activity and communication transmission found activation during real-time SoI in the prefrontal cortex, regions where EFs are located (Redcay & Schilbach, 2019, see also Jones & Graff-Radford, 2021).

So far, only a few experimental studies have investigated whether acute SoI benefits EFs. These studies show that healthy adults' EFs can be improved even by brief (10-min) SoIs (Ybarra et al., 2008, 2011), such as through intellectual discussions (Ybarra et al., 2008), online interactions involving active mental modeling (Ybarra & Winkielman, 2012), simple "getting-to-know-you" conversations, and cooperative rather than competitive SoI sessions (Ybarra, Winkielman, Yeh, Burnstein, & Kavanagh, 2011). Looking deeper into mechanisms of enhanced EFs due to SoI, previous studies have investigated joint actions—a type of SoI involving at least two individuals that coordinate their actions in space and time to achieve a common task goal (Sebanz & Bekkering, 2006). Results show that cooperation and sharing task goals influence participants' cognitive processes in a subsequent shared visual Simon task (Liepelt & Raab, 2021).

In PA and cognition research, the role of SoI requires further investigation, as noted in a recent systematic meta-review and realist synthesis aimed at identifying the role of contextual factors in the PA-cognition relation (Pesce et al., 2023). The role of SoI as a cognition enhancer has been mainly addressed in longitudinal non-interventional PA studies (Cohn-Schwartz, 2020). In acute PA-cognition studies, to our knowledge, SoI is under-investigated and mainly considered as a mere potential confounder (Best, 2012; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009). Indeed, Pesce et al. (2009) demonstrated better cognitive outcomes after group activities with a greater extent of SoI; however, the effect of SoI could not be decoupled from the level of cognitive engagement inherent in the PA games.

Evaluating the effect of cognitive stimulation from PA, either coupled with or decoupled from that elicited by SoI, seems crucial to further our understanding of the exercise-cognition interaction. This is particularly relevant because both may stimulate brain areas responsible for EFs, and these effects may persist after the activity. Unfortunately, previous research has used a variety of individual and group activities, mostly neglecting the fact that these activities differ in many variables and that group PA also differs in the level of SoI.

Therefore, to maximize the benefits for EFs, it is crucial to systematically investigate the single and combined effects of SoI and PA, which was the aim of the current study. Against the background of the above-mentioned empirical evidence on the effects of acute PA on inhibition (Pontifex et al., 2019) and the effects of acute SoI on EFs (Ybarra et al., 2008, 2011; Ybarra & Winkielman, 2012), we hypothesized to find a positive main and interaction effect of acute PA and SoI on inhibition.

2. Methods

2.1. Design

Data were collected using a 2 (SoI/no SoI) × 2 (PA/no PA) within-subject design with a post-measurement of inhibition (Pontifex et al., 2019). First, all participants underwent a baseline measurement. In the following four weeks, at the same time and on the same days of the week, participants underwent four conditions (see experimental conditions for details) that varied in terms of PA (PA/no PA) and SoI (SoI/no SoI). Experimental conditions were carried out in a counterbalanced order to exclude a systematic coupling of carry-over effects with experimental conditions (Pontifex et al., 2019). In SoI conditions, participants were active with the same partner to avoid confounding variables (Halperin, Pyne, & Martin, 2015). Participants were randomly assigned to another participant of the same gender, as the presence of a partner of the other gender might influence cognitive performance (Karremans, Verwijmeren, Pronk, & Reitsma, 2009). The experimental conditions were conducted using the exergame scenario *Sphery Racer* (Martin-Niedecken, Segura, Rogers, Niedecken, & Vidal, 2019) in different variations: 1) the original physically active version, and 2) a non-physically active version which was played via keyboard.

2.2. Participants

Based on our power analysis (see Supplementary Material for details) and counterbalancing requirements, a total of 96 sports science students ($M = 20.51$, $SD = 1.73$, ♀ = 48) from the University of Bern, Switzerland, participated in this study (for background characteristics, see Table 1; for a description of background variables, see the Supplementary Material). The participants were informed about the study, its methods and agreed (provided written informed consent) to participate. Data were collected pseudonymously, and the Ethics Commission of the Faculty of Human Sciences at the University of Bern granted ethical approval for this study (No. 2020-10-00003).

2.3. Procedure

In the baseline measurement, participants completed a questionnaire on background variables (see Supplementary Material). Subsequently, body weight and size were measured, and HRmax was calculated using the formula HRmax = 211 – (0.64 × age) (Nes, Janszky, Wisløff, Støylen, & Karlsen, 2013).

For familiarization, participants performed the computer-based Eriksen Flanker Task (Eriksen & Eriksen, 1974), followed by a 5-min exergame session. Exergames are active video games that provide an enjoyable experience by combining cognitive and physical challenges (Benzing & Schmidt, 2018). They allow for controlling PA characteristics while maintaining high internal and ecological validity (Benzing et al., 2016).

Over four weeks, participants performed a Sphery Racer session of 15 min weekly, a duration known to effectively enhance EFs (Anzeneder, Zehnder, Martin-Niedecken et al., 2023). It was played either alone or in pairs depending on the condition, preceded by a 5-min warm-up and a tutorial. Participants completed a questionnaire about physical exertion, cognitive demands, stress, pleasure, and arousal before (t0), during (t1), and after (t2) the exergame session. The 15-min exergame session was paused for a brief assessment break after 5 min (t1). In SoI conditions, participants answered additional questions about perceived SoI (Kort, Poels, & Ijsselsteijn, 2007). During all assessments, participants wore heart rate (HR) monitoring equipment. In the PA conditions, HR was maintained at a level that corresponded to moderate exercise intensity (70% HRmax). The Eriksen Flanker Task (Eriksen & Eriksen, 1974) was completed alone immediately after playing the (exer-)game. The intervention took place in the laboratory of the institute of Sport Science at the University of Bern.

Table 1
Participant's background characteristics.

Background variables		*M* (*SD*)
Age (years)		20.51 (1.73)
Gender (% female)		50%
Body mass index (kg/m^2)		21.88 (1.98)
HRmax		197.68 (2.57)
Physical activity behavior (min/week)		433.46 (197.41)
Need for cognition [-3–3]		−0.32 (0.38)
Need for affect [-3–3]	Approach	0.57 (0.82)
	Avoidance	−1.04 (0.95)
Habitual stress [0–4]		1.92 (0.35)
Self-reported executive functioning [1–5]		2.51 (0.39)
Personality traits [1–5]	Extraversion	2.78 (0.31)
	Agreeableness	2.90 (0.22)
Motives/goals [1–5]	Contact	3.35 (0.90)
	Competition/performance	3.25 (0.77)
	Activation/enjoyment	3.93 (0.65)
	Distraction/catharsis	3.40 (0.94)
	Figure/appearance	2.26 (0.81)
	Fitness/health	4.10 (0.66)
	Aesthetics	3.14 (1.16)

Note. M = Mean, *SD* = Standard deviation, HRmax = Maximal heart rate.

2.4. Experimental conditions

Participants played the different versions of the exergame *Sphery Racer*, an exergame scenario that was originally designed to be played on the ExerCube platform in which cognitively challenging motor tasks had to be performed (Martin-Niedecken, Segura, et al., 2019). In the *Sphery Racer*, participants were immersed in an underwater race on a screen. In the physically active condition, participants wore tracking sensors (HTC Vive, Seattle, United States). For the sedentary conditions, the *Sphery Racer* was played without physical movement and by using a keyboard. On the virtual racetrack, participants passed through different colored gates, each representing a distinct movement (e.g., deep lunges, touching the left or right wall). For each successful movement, the participant(s) collected points, with timing and correctness being crucial. Correct movements within a certain timeframe led to higher levels and speed. However, if the sensor-measured 70% HRmax was exceeded or the participant(s) made errors (e.g., delayed or missed actions), the *Sphery Racer* reduced speed and task complexity. Conversely, if the HRmax remained below 70% or no errors were made, the *Sphery Racer* sped up and the tasks became more complex. In this way, all participants were challenged optimally at their cognitive and fitness levels. The four conditions varied in PA (PA/no PA) and SoI (SoI/no SoI; see Fig. 1).

a *Sedentary single condition (no SoI/no PA)*. The participants played the game alone in a seated position using the keyboard. For each movement, the participant had to press a specific combination of two keys simultaneously.
b *Physical activity condition (no SoI/PA)*. Participants performed the exergame alone. They controlled the exergame with bodily movements.
c *Social interaction condition (SoI/no PA)*. Participants played the game with a partner in a seated position using the keyboard. They jointly controlled the game with combinations of synchronous keystrokes.
d *Social interaction and physical activity condition (SoI/PA)*. Participants performed the exergame with a partner. They controlled the exergame by performing bodily movements together (Martin-Niedecken, Segura, et al., 2019).

2.5. Measures

2.5.1. Inhibition

The Eriksen Flanker Task (Eriksen & Eriksen, 1974) is a widely-used computerized task employed to assess inhibition response. The current study implemented the task using the Inquisit 5 platform by Millisecond, Software, Seattle, WA (see Supplementary Materials for details). The Eriksen Flanker Task has demonstrated acceptable psychometric properties (Zelazo et al., 2014).

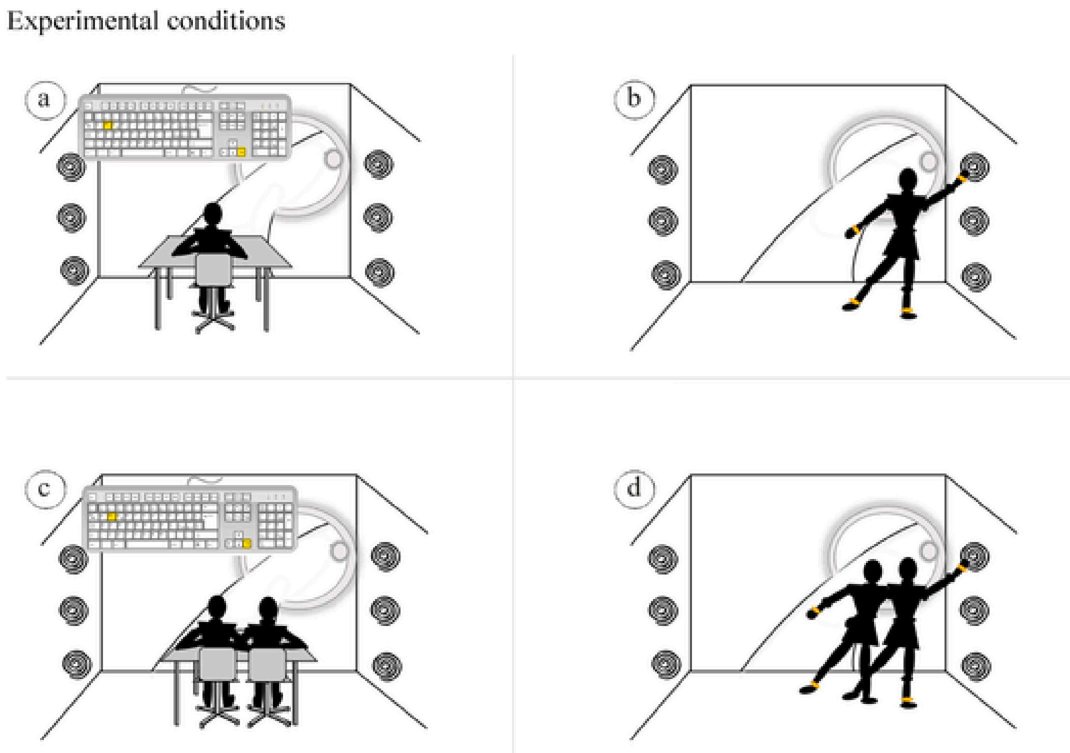

Fig. 1. Overview of the four experimental conditions, which differ in terms of physical activity and social interaction: a. no SoI/no PA = Sedentary single condition; b. no SoI/PA = Physical activity condition; c. SoI/no PA = Social interaction condition; d. SoI/PA = Social interaction and physical activity condition. In the PA conditions (conditions b and d), participants wore sensors on their wrists and ankles and engaged in tasks such as touching the upper right wall. In the SoI/PA condition, each participant wore two sensors on the right or left side; in the no SoI/PA condition, each participant wore four sensors. In the no PA conditions (conditions a and c) participants controlled the game using a keyboard, where they had to press different key combinations such as "right" and "z" simultaneously. Socially interactive conditions (conditions c and d) involved collaborative participation.

2.5.2. Manipulation check variables

Heart rate and physical exertion. HR was measured and maintained at an average of 70% HRmax during all *Sphery Racer* sessions using the Polar Team 2 sensors and straps (Polar Electro Oy, Kempele, Finland). Moreover, perceived physical exertion was assessed using the Borg Rating Scale of Perceived Exertion (RPE Scale) (Borg, 1982). The item was "How exhausting was the previous activity for your body?", with response format ranging from 6 (no exertion at all) to 20 (maximal exertion). The RPE Scale is a well-established method for assessing physical exertion (Arney et al., 2019).

2.5.3. Control variables

As an indicator of *cognitive demands*, we assessed the perceived cognitive engagement–a single item adapted from the RPE Scale (Borg, 1982). The item was "How exhausting was the previous activity for your brain?". The response format was from 6 (no demands at all) to 20 (maximal demands). This item has not yet been validated but has been used in previous studies in children and adolescents (Benzing et al., 2016; Schmidt et al., 2016).

Arousal and stress. Arousal was rated using the Feeling Scale (Hardy & Rejeski, 2016) an 11-point scale ranging from −5 (very bad) to 5 (very good). Stress symptoms were measured with a single item (Elo, Leppänen, & Jahkola, 2003) which was introduced with "Stress means a situation in which a person feels tense, restless, nervous, or anxious. Have you been feeling this kind of stress now?". In contrast to the original question about stress perception over a few multiple days, this question was adapted to ask for the present state. Response format ranged from 1 (not at all) to 5 (very much). Appropriate psychometric properties have been demonstrated for the Feeling Scale (Hardy & Rejeski, 2016) and the single-item stress symptom measure (Elo et al., 2003).

Social presence in gaming. The Social Presence in Gaming Questionnaire (SPGQ;Kort et al., 2007) was used to analyze SoI behavior during gaming, which assessed the awareness and relationship with the partner. Another study used this questionnaire to explore exergames in multi- and dual-player modes (Martin-Niedecken, Rogers, Turmo Vidal, Mekler, & Márquez Segura, 2019). The questionnaire consists of 3 categories with 21 items. For the present study, only the category 'behavioral engagement' was used, which comprised 8 items. An example item is, "My actions depended on the other's actions". The response format was from 0 (not at all) to 4 (extremely). Appropriate psychometric properties have been demonstrated (Kort et al., 2007).

3. Statistical analysis

Statistical analyses were conducted using SPSS (version 28.0; SPSS Inc., Chicago, IL, USA). For the manipulation check and control variables (perceived stress, physical exertion, cognitive demands, arousal, social presence in gaming), one-way repeated measures ANOVAs were performed with Greenhouse-Geisser or Epsilon-Huynh-Feldt adjustment in cases of violations of sphericity. A two-way repeated measures factorial ANOVA was calculated to analyze the within-subject factors of PA, SoI, and their combination on inhibition response. Post-hoc Bonferroni-adjusted pairwise comparisons were conducted to analyze the effects of SoI and PA (see Supplementary Material for further details on statistical analyses). The dependent variables were accuracy rates (% errors) and RTs. Effect sizes were quantified using η^2_p (small = 0.01, medium = 0.06, large = 0.14) (Cohen, 1988). Statistical significance was set at $p < .05$. A total of 0.37% of the values were missing randomly, due to the participants leaving fields blank in questionnaires. The MCAR test (Little & Rubin, 2002) indicated a non-significant value ($\chi^2(1256) = 1244.30$, $p = .587$). Therefore, the expectation-maximization algorithm was used for single-imputation.

4. Results

4.1. Manipulation check and control variables

Results showed significant differences in the manipulation check variables—physical exertion and average HR—and the control variables—cognitive exertion, arousal, stress, and social presence in gaming—across the four conditions (see Fig. 2 and Table 2; for a description of the additional SoI questions, see the Supplementary Material). Taken together, manipulation seems partially succeeded: As expected, physical exertion (at t1 and t2) and average HR were higher in both PA conditions than in no PA conditions. Unexpectedly, cognitive engagement was rated higher in the sedentary single condition compared to the other conditions. Furthermore, participants found the sedentary single condition to be more enjoyable than both PA conditions. In the SoI condition, there were lower stress levels at t1 compared to the sedentary single condition and a lower arousal level before (t0) playing the game compared to the other conditions. After (t2) playing the (exer-)game, arousal was higher in the SoI/PA condition than in the sedentary single condition. Social presence in gaming was rated higher in the SoI and PA condition than in the SoI condition.

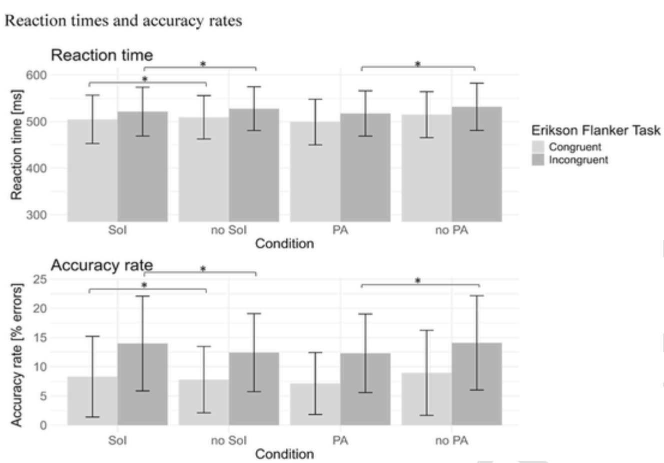

Fig. 2. Development of (a) arousal, (b) RCE = Rating of cognitive exertion, (c) RPE = Rating of perceived exertion, and (d) perceived stress among the four conditions over time (before t0; during t1; after t2). *Note.* no SoI/no PA = Sedentary single condition; no SoI/PA = Physical activity condition; SoI/no PA = Social interaction condition; SoI/PA = Social interaction and physical activity condition. Error bars indicate standard deviations (Bonferroni, adjusted $p = .013$).

4.2. Main analyses

Main analyses (see Fig. 3 and Table 3) revealed faster RTs in congruent trials following PA compared to no PA conditions ($F(1, 95) = 21.44$, $p < .001$, $\eta^2_p = 0.184$). Additionally, accuracy rates were higher after PA compared to no PA conditions ($F(1, 95) = 11.60$, $p < .001$, $\eta^2_p = 0.109$). No differences in RTs or accuracy were found for SoI and no SoI conditions (RTs: $p = .158$, $\eta^2_p = 0.021$; accuracy rates: $p = .211$, $\eta^2_p = 0.016$). Additionally, there was no interaction effect of SoI and PA (RTs: $p = .570$, $\eta^2_p = .003$; accuracy rates: $p = .155$, $\eta^2_p = 0.021$).

Regarding incongruent trials, participants benefited from PA in terms of faster RTs ($F(1, 95) = 19.34$, $p < .001$, $\eta^2_p = 0.169$) and higher accuracy rates ($F(1, 95) = 9.41$, $p = .003$, $\eta^2_p = 0.090$). Regarding SoI, participants had faster RTs after SoI ($F(1, 95) = 4.11$, $p = .045$, $\eta^2_p = 0.041$) but made more errors ($F(1, 95) = 15.43$, $p < .001$, $\eta^2_p = 0.140$) than in no SoI conditions. No significant interaction effects were found for accuracy rates ($p = .061$, $\eta^2_p = 0.036$) and RTs ($p = .513$, $\eta^2_p = 0.005$).

5. Discussion

We investigated the effects of acute PA (exergaming) and SoI on inhibition and hypothesized to find positive main and interaction effects of PA and SoI on inhibition performance. The results only partially confirmed our hypotheses: Main but not interactive effects of PA and SoI on inhibition were found. Inhibition performance was faster and more accurate in both congruent and incongruent trials after acute bouts of exergaming with and without SoI, suggesting that inhibition response was

Table 2
Manipulation check and control variables across three measurement points (before t0; during t1; after t2) in the four conditions.

		no SoI/no PA	no SoI/PA	SoI/no PA	SoI/PA	F(3, 285)	p	η^2_p	
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*Huynh-Feldt			
Arousal [-5–5]	t0	2.15 (1.56)[a]	2.02 (1.47)[a]	1.53 (1.60)[b]	2.00 (1.47)[a]	5.25	0.002	0.052	a > b
	t1	2.01 (1.53)	2.08 (1.45)	2.08 (1.49)	2.17 (1.43)	0.29	0.831	0.003	
	t2	1.88 (1.45)[a]	2.29 (1.55)[ab]	2.29 (1.47)[ab]	2.37 (1.38)[b]	3.75	0.011	0.038	a < b
RPE [6–20]	t0	7.85 (2.48)	7.99 (2.52)	7.84 (2.29)	8.16 (2.92)	F(2.80, 265.62) 0.583*	0.615	0.006	
	t1	7.04 (1.41)[a]	12.18 (1.85)[b]	6.95 (1.34)[a]	11.18 (2.37)[c]	F(2.71, 257.58) 311.50*	<0.001	0.766	b > c > a
	t2	7.31 (1.59)[a]	13.54 (1.46)[b]	7.07 (1.39)[a]	12.58 (2.28)[c]	F(2.74, 259.83) 502.29*	<0.001	0.841	b > c > a
RCE [6–20]	t0	8.31 (2.57)	8.17 (2.36)	8.13 (2.42)	7.95 (2.18)	0.64	0.593	0.007	
	t1	12.77 (2.26)[a]	10.60 (2.39)[b]	11.35 (2.39)[c]	11.11 (2.41)[bc]	24.89	<0.001	0.208	a > c > b
	t2	12.74 (2.40)[a]	11.06 (2.38)[b]	11.39 (2.64)[b]	11.63 (2.31)[b]	15.05	<. 001	0.137	a > b
Stress [1–5]	t0	1.83 (0.91)	1.98 (0.81)	1.85 (0.86)	1.75 (0.78)	2.26	0.081	0.023	
	t1	2.26 (0.86)[a]	2.10 (0.79)[ab]	1.98 (0.73)[b]	2.03 (0.81)[ab]	3.91	0.009	0.040	a > b
	t2	2.26 (0.85)	2.14 (0.87)	2.03 (0.75)	2.22 (1.01)	2.18	0.091	0.022	
Average HR		78.63 (13.50)[a]	134.36 (15.30)[b]	83.49 (18.46)[c]	130.54 (13.47)[b]	F(2.53, 240.48) = 440.78*	<0.001	0.823	b > c > a
Social presence in gaming [0–4]				2.25 (1.09)	2.76 (1.00)	22.62	<0.001	0.196	

Note. M = Mean; *SD* = Standard deviation; RPE = Rating of perceived exertion. HR = Heart rate. RCE = Rating of cognitive exertion. no SoI/no PA = Sedentary single condition; no SoI/PA = Physical activity condition; SoI/no PA = Social interaction condition; SoI/PA = Social interaction and physical activity condition. a,b,c - For significant post-hoc tests the same letter indicates that the groups do not differ significantly from each other (Bonferroni, adjusted $p = .013$).

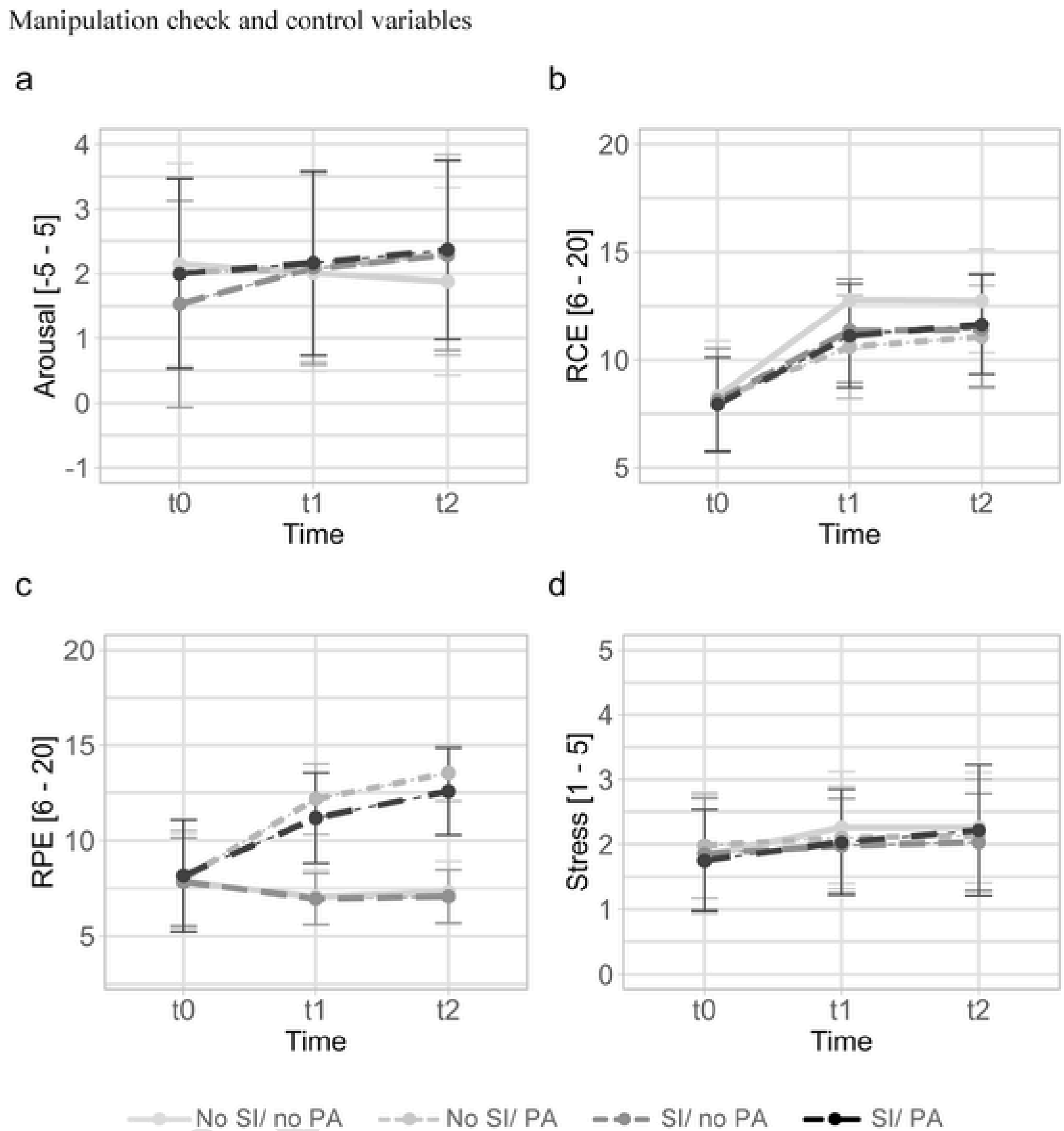

Fig. 3. Reaction times and accuracy rates across conditions vary by social interaction and physical activity. Error bars indicate standard deviation (Bonferroni, adjusted $p = .025$).

transiently improved by exergaming regardless of the SoI component. Concerning SoI, participants reacted faster but had lower accuracy after the SoI conditions, indicating a speed-accuracy trade-off elicited by both physically active and inactive SoI conditions. These independent effects of PA and SoI challenge prior assumptions that adding SoI to the PA bout might bring additional benefits for EFs (Best, 2010). Specifically, our results do not confirm the assumption of the cognitive stimulation hypothesis, that acute socially interactive PA benefits cognition due to the cognitive challenge inherent in SoI (Best, 2010; Diamond & Ling, 2019; Pesce et al., 2009)

Results highlight that SoI in the context of PA neither amplifies nor buffers the transient improvement of inhibition performance observed after the participants engaged in an exergaming bout designed to reach an individually appropriate level of cognitive challenge (Anzeneder, Zehnder, Martin-Niedecken et al., 2023). Instead, SoI seems to render inhibition performance faster and less accurate.

In terms of performance speed (RT), the facilitative effects of PA and SoI might be independently positive, since participants showed faster responses after engaging in PA (Pontifex et al., 2019) or SoI (Ybarra et al., 2008) without any loss of accuracy (McMorris & Hale, 2012; Ybarra et al., 2008, 2011). This improvement may result from coordinated actions; individuals enter the "we-mode", a collective mindset where individuals view their actions as a joint mission and form a unit (Gallotti & Frith, 2013). Achieving a collective goal necessitates orchestrating individuals' actions with millisecond-level accuracy, requiring high cognitive demands (Curioni, 2022). This was the aim to achieve in the SoI conditions, where communication and timing synchronization of movements were required.

To gain a greater understanding of how SoI within PA affected individuals, we performed extensive manipulation checks. Interestingly, the manipulation checks showed that the SoI conditions were perceived as similar or even more cognitively demanding than the no SoI conditions. Manipulation checks also revealed that SoI induced lower cognitive demand (SoI/PA) but higher arousal compared to no SoI conditions. Speculatively, the low cognitive challenge may have led the participants to allocate less attention and make more errors, while the enhanced arousal caused by SoI may have led to the typical effect of RT facilitation (Lambourne & Tomporowski, 2010). One possible explana-

Table 3
Descriptive statistics including reaction times and accuracy rates.

Experimental conditions (N = 96)		RTs in ms	Accuracy rates in % errors
		M (*SD*)	*M* (*SD*)
Social interaction	congruent	504.81 (51.81)	8.29 (6.90)
	incongruent	521.31 (52.37)	13.98 (8.11)
No social interaction	congruent	509.22 (46.49)	7.79 (5.67)
	incongruent	527.78 (46.94)	12.41 (6.67)
Physical activity	congruent	499.09 (48.96)	7.13 (5.30)
	incongruent	517.35 (48.62)	12.30 (6.72)
No physical activity	congruent	514.94 (49.33)	8.95 (7.27)
	incongruent	531.75 (50.70)	14.09 (8.07)

This table includes reaction times and accuracy rates of congruent and incongruent trials of the Eriksen Flanker Task in physically active and socially interactive conditions.
Each factor includes mean values of two experimental conditions (e.g., Mean RT of social interaction = mean RT (SoI/PA + SoI/no PA); mean RT of no social interaction = mean RT (no SoI/PA + no SoI/no PA); mean RT of physical activity = mean RT (no SoI/PA + SoI/no PA); mean RT of no physical activity = mean RT (no SoI/no PA + SoI/no PA).
Note. M = Mean, *SD* = Standard deviation.

tion for the lower cognitive demands perceived in the SoI conditions is that joint actions may increase the uncertainty of the task process (Navarro, Quijano, & Berger, 2011) and action outcomes (Curioni, 2022), potentially amplifying susceptibility to errors. Consequently, poorly coordinated movements (e.g., delayed actions or insufficient interaction proximity) prompt an immediate deceleration of the (exer-)game and result in simpler and less cognitively demanding actions. This may have led individuals to perceive the (exer-)game's dual-playing mode to be less cognitively demanding. Speculatively, this blend of acute PA and SoI may not be cognitively stimulating enough, which is why we could not find an interaction effect of PA and SoI on inhibition. Taken together, manipulations were successful; however, acute cognitively challenging PA may have caused a ceiling effect that allowed only minimal inhibition improvement after the participants played the exergame in a socially interactive manner. Therefore, further studies are needed that investigate SoI in PAs that are less cognitively challenging.

In addition, this study could only partially support our hypothesis that SoI improves inhibition performance. Results show that reaction times shortened, but accuracy rates decreased with SoI. This contrasts previous findings demonstrating improved EFs after a 10-min SoI session (Ybarra et al., 2008, 2011). The realized SoI condition of the current study differs from those in previous SoI research: The SoI used in the current study was designed to trigger a series of fragmented and swiftly concluded task-driven micro-conversations akin to the nature of team sports interactions (Le Couteur & Feo, 2011). This conversational fragmentation, with fast-paced execution and management of numerous roles and tasks (Ishak, 2017), differs from previous research, which investigated continuous and sustained SoIs, likely characterized by an ongoing exchange of thoughts and creating a shared mental model (Ybarra et al., 2008, 2011; Ybarra & Winkielman, 2012). Other studies explored more demanding SoI, such as inefficient and effortful social coordination tasks (Finkel et al., 2006), revealing that individuals undergo cognitive exhaustion, resulting in lower cognitive performance. In this context, Finkel et al. (2006) hypothesized that cognitive exhaustion arises when social coordination is less efficient and more energy-demanding than individual task performance, impacting subsequent cognitive tasks. Speculatively, this may also apply to our SoI conditions, where participants may invest more cognitive resources and be less efficient when undertaking the task alone.

Regarding the effects of cognitively challenging acute PA, findings of the current study indicate that 15 min of moderate-intensity PA led to better inhibition compared to the sedentary single conditions. This result is in line with previous meta-analyses recommending a moderate intensity of 11–20 min for improving inhibition performance (Chang et al., 2012, 2015). Unlike a prior systematic review that found small effects in young adults (Ludyga, Gerber, Brand, Holsboer-Trachsler, & Pühse, 2016), the current study revealed medium to large effect sizes. This may be due to the cognitively challenging, highly adaptive and individualized PA (Leisman, Moustafa, & Shafir, 2016), which seems necessary to achieve higher improvements in young adults' inhibition performance (Smid, Karbach, & Steinbeis, 2020).

Intriguingly, the sedentary single condition emerged as the most cognitively demanding condition in the current study. This is probably due to participants using keyboard inputs to control the game, which allowed them to navigate the game at an accelerated pace compared to performing physical movements, which take more time. Consequently, the used control condition was a stringent comparison due to its relatively high cognitive demand. We intended to specifically manipulate PA and SoI while maintaining a high cognitive demand in all conditions. Future research could explore the relationship between SoI and cognitive demand in a 2 × 2 factorial design to disentangle these factors and their influence on cognitive performance.

Although this study was a first step toward gaining insights into the factors enhancing the benefits of acute PA on EFs, there are some practical implications to consider. First, this study showed that qualitative characteristics of PA do matter for the effects on cognitive performance. The social domain is one characteristic that needs to be considered in practice and research. Second, from the results of our study, we derive that also negative effects on cognitive performance are possible after SoI (e.g., depletion effect) and may depend on the form of SoI. Therefore, when implementing PA with the goal of immediate improvements, for example in a university setting, the lectures should include PA breaks and phases of SoI that are carefully designed to represent an optimal challenge level that does not turn into depletion. Of note, more research is needed to derive definitive conclusions for practice and develop targeted PA interventions to improve both transient cognitive states and long-term cognitive health.

6. Limitations and further directions

The current study has limitations that need to be acknowledged. Our focus was solely on inhibition. Further studies should also systematically explore the other core EFs (cognitive flexibility and working memory), as well as higher-level EFs (e.g., planning, reasoning) and non-EFs (e.g., long-term memory, visuospatial attention; Diamond & Ling, 2019; Dias et al., 2024). Moreover, we did not objectively record participants' SoI behaviors, limiting our ability to capture and analyze the quantity and quality of SoI unambiguously. Future studies could use video recording methods to analyze SoI (Hadley et al., 2022).

7. Conclusion

This study empirically investigates a widely held assumption that SoI during acute PA improves EFs. Although theories, such as the cognitive stimulation hypothesis suggest benefits from socially interactive PA, the findings of the current study indicate that the issue is more complex: SoI can lead to negative effects on cognitive performance (faster reaction times but reduced accuracy), while acute PA can improve inhibition performance regardless of SoI (faster reaction times and higher accuracy). This effect may be attributed to the high cognitive demands inherent in the exergame, potentially limiting SoI's capacity to enhance EF performance. Future studies should systematically investigate the influence of SoI and cognitive demands during acute PA sessions. Understanding the interplay between SoI, cognitive demands, and other contextual factors may uncover conditions for maximizing EFs' gains, informing targeted interventions.

CRediT authorship contribution statement

Cäcilia Zehnder: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation. **Marion Gasser:** Writing – review & editing, Project administration, Formal analysis, Data curation. **Sofia Anzeneder:** Writing – review & editing, Methodology. **Anna Lisa Martin-Niedecken:** Writing – review & editing, Visualization, Methodology. **Caterina Pesce:** Writing – review & editing, Methodology. **Mirko Schmidt:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Valentin Benzing:** Writing – review & editing, Resources, Methodology, Conceptualization.

Declaration of competing interest

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

Mirko Schmidt reports financial support was provided by Swiss National Science Foundation (SNSF). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mhpa.2024.100640.

References

Anzeneder, S., Zehnder, C., Martin-Niedecken, A.L., Schmidt, M., & Benzing, V. (2023). *Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? Psychology of Sport and Exercise*, *66*, 102404. https://doi.org/10.1016/j.psychsport.2023.102404.

Anzeneder, S., Zehnder, C., Schmid, J., Martin-Niedecken, A.L., Schmidt, M., & Benzing, V. (2023). *Dose–response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. Scandinavian Journal of Medicine & Science in Sports*, *33*(8), 1439–1451. https://doi.org/10.1111/sms.14370.

Arney, B.E., Glover, R., Fusco, A., Cortis, C., de Koning, J.J., Erp, T. van, et al. (2019). *Comparison of RPE (rating of perceived exertion) scales for session RPE. International Journal of Sports Physiology and Performance*, *14*(7), 994–996. https://doi.org/10.1123/ijspp.2018-0637.

Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). *Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. PLoS One*, *11*(12), 1–15. https://doi.org/10.1371/journal.pone.0167501.

Benzing, V., & Schmidt, M. (2018). *Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. Journal of Clinical Medicine*, *7*(11), 422. https://doi.org/10.3390/jcm7110422.

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

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

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

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

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

Cohen, J. (1988). *Statistical power analysis for the behavioral science* (2nd ed.). Erlbaum Associates.

Cohn-Schwartz, E. (2020). *Pathways from social activities to cognitive functioning: The role of physical activity and mental health. Innovation in Aging*, *4*(3), 1–10. https://doi.org/10.1093/geroni/igaa015.

Cristofori, I., Cohen-Zimerman, S., & Grafman, J. (2019). Executive functions. *Handbook of clinical neurology*: *Vol. 163* (1st ed.). Elsevier B.V. https://doi.org/10.1016/B978-0-12-804281-6.00011-2.

Curioni, A. (2022). *What makes us act together? On the cognitive models supporting humans' decisions for joint action. Frontiers in Integrative Neuroscience*, *16*, 1–7. https://doi.org/10.3389/fnint.2022.900527.

Darker, C.D., Larkin, M., & French, D.P. (2007). *An exploration of walking behaviour — an interpretative phenomenological approach. Social Science & Medicine*, *65*, 2172–2183. https://doi.org/10.1016/j.socscimed.2007.06.029.

De Jaegher, H., Di Paolo, E., & Gallagher, S. (2010). *Can social interaction constitute social cognition? Trends in Cognitive Sciences*, *14*(10), 441–447. https://doi.org/10.1016/j.tics.2010.06.009.

Diamond, A., & Lee, K. (2011). *Interventions shown to aid executive function development in children 4 to 12 years old. Science*, *333*(6045), 959–964. https://doi.org/10.1126/science.1204529.

Diamond, A., & Ling, D.S. (2019). Review of the evidence on, and fundamental questions about, efforts to improve executive functions, including working memory. In J.M., Novick, M.F., Bunting, M.R., Dougherty, & R.W., Engle (Eds.), *Cognitive and working memory training: Perspectives from psychology, neuroscience, and human development* (pp. 143–431). https://doi.org/10.1093/oso/9780199974467.003.0008.

Dias, N.M., Helsdingen, I.E., de Lins, E.K.R.M., Etcheverria, C.E., de Araújo Dechen, V., Steffen, L., et al. (2024). *Executive functions beyond the "holy trinity": A scoping review. Neuropsychology*, *38*(2), 107–125. https://doi.org/10.1037/NEU0000922.

Elo, A.A., Leppänen, A., Jahkola, A., & Scandinavian, S. (2003). *Validity of a single-item measure of stress symptoms. Scandinavian Journal of Work, Environment & Health*, *29*(6), 444–451. https://doi.org/10.5271/sjweh.752.

Erickson, K.I., Hillman, C., Stillman, C.M., Ballard, R.M., Bloodgood, B., Conroy, D.E., et al. (2019). *Physical activity, cognition, and brain outcomes: A review of the 2018 physical activity guidelines. Medicine & Science in Sports & Exercise*, *51*(6), 1242–1251. https://doi.org/10.1249/MSS.0000000000001936.

Eriksen, B.A., & Eriksen, C.W. (1974). *Effects of noise letters upon the identification of a target letter in a nonsearch task. Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267.

Finkel, E.J., Campbell, W.K., Brunell, A.B., Dalton, A.N., Chartrand, T.L., & Scarbeck, S.J. (2006). *High-maintenance interaction: Inefficient social coordination impairs self-regulation. Journal of Personality and Social Psychology*, *91*, 456–475. https://doi.org/10.1037/0022-3514.91.3.456.

Gallotti, M., & Frith, C.D. (2013). *Social cognition in the we-mode. Trends in Cognitive Sciences*, *17*(4), 160–165. https://doi.org/10.1016/j.tics.2013.02.002.

Hadley, L.V., Naylor, G., & Hamilton, A.F. (2022). *A review of theories and methods in the science of face-to-face social interaction. Nature Reviews Psychology*, *1*, 42–54. https://doi.org/10.1038/s44159-021-00008-w.

Halperin, I., Pyne, D.B., & Martin, D.T. (2015). *Threats to internal validity in exercise science: A review of overlooked confounding variables. International Journal of Sports Physiology and Performance*, *10*(7), 823–829. https://doi.org/10.1123/IJSPP.2014-0566.

Hardy, C.J., & Rejeski, W.J. (2016). *Not what, but how one feels: The measurement of affect during exercise. Journal of Sport & Exercise Psychology*, *11*(3), 304–317. https://doi.org/10.1123/jsep.11.3.304.

Haverkamp, B.F., Wiersma, R., Vertessen, K., van Ewijk, H., Oosterlaan, J., & Hartman, E. (2020). *Effects of physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults: A meta-analysis. Journal of Sports Sciences*, *38*(23), 2637–2660. https://doi.org/10.1080/02640414.2020.1794763.

Heilmann, F., Weinberg, H., & Wollny, R. (2022). *The impact of practicing open- vs. closed-skill sports on executive functions: A meta-analytic and systematic review with a focus on characteristics of sports. Brain Sciences*, *12*(8), 1071. https://doi.org/10.3390/brainsci12081071.

Ishak, A. (2017). *Communication in sports teams: A review. Communication Research Trends*, *36*(4), 4–38.

Jones, D.T., & Graff-Radford, J. (2021). *Executive dysfunction and the prefrontal cortex. American Academy of Neurology*, *27*(6), 1586–1601. https://doi.org/10.1212/CON.0000000000001009.

Karr, J.E., Areshenkoff, C.N., Rast, P., Hofer, S.M., Iverson, G.L., & Garcia-Barrera, M.A. (2018). *The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. Psychological Bulletin*, *144*(11), 1147–1185. https://doi.org/10.1037/bul0000160.

Karremans, J.C., Verwijmeren, T., Pronk, T.M., & Reitsma, M. (2009). *Interacting with women can impair men's cognitive functioning. Journal of Experimental Social Psychology*, *45*(4), 1041–1044. https://doi.org/10.1016/j.jesp.2009.05.004.

Kort, Y. A. W. De, Poels, K., & Ijsselsteijn, W.A. (2007). *Digital games as social presence technology: Development of the social presence in gaming questionnaire (SPGQ). Presence*, 1–9.

Krach, S., Paulus, F.M., Bodden, M., & Kircher, T. (2010). *The rewarding nature of social interactions. Frontiers in Behavioral Neuroscience*, *4*(22), 1–3. https://doi.org/10.3389/fnbeh.2010.00022.

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

Lanooij, S.D., Eisel, U.L., Drinkenburg, W.H., van der Zee, E.A., & Kas, M.J. (2022). *Influencing cognitive performance via social interactions: A novel therapeutic approach for brain disorders based on neuroanatomical mapping? Molecular Psychiatry*, *28*, 28–33. https://doi.org/10.1038/s41380-022-01698-1.

Le Couteur, A., & Feo, R. (2011). *Real-time communication during play : Analysis of team-mates ' talk and interaction. Psychology of Sport and Exercise*, *12*(2), 124–134. https://

doi.org/10.1016/j.psychsport.2010.07.003.
Leisman, G., Moustafa, A.A., & Shafir, T. (2016). *Thinking, walking, talking: Integratory motor and cognitive brain function. Frontiers in Public Health*, *4*, 1–19. https://doi.org/10.3389/fpubh.2016.00094.
Lewis, C., & Carpendale, J.I.M. (2009). Introduction: Links between social interaction and executive Function. In C., Lewis, & J.I., Carpendale (Eds.), *Social interaction and the development of executive function (Issue 123* (pp. 1–15). https://doi.org/10.1002/cd. New Directions in Child and Adolescent Development.
Liepelt, R., & Raab, M. (2021). *Metacontrol and joint action: How shared goals transfer from one task to another? Psychological Research*, *85*(7), 2769–2781. https://doi.org/10.1007/s00426-020-01443-9.
Little, R.J.A., & Rubin, D.B. (2002). Statistical analysis with missing data. In D.J., Balding, P., Bloomfield, N.A., Cressie, D.W., Scott, A.F., Smith, & T., Jozef (Eds.), *Statistical analysis with missing data* (2nd ed.). Wiley Series in Probability and Statistics. https://doi.org/10.1002/9781119013563.
Lubans, D.R., Leathy, A.A., Mavilidi, F., & Valkenborghs, S.R. (2021). Physical activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. In S., Andersen (Ed.), *Sensitive periods of brain development and preventive interventions* (pp. 103–124). Springer. https://doi.org/10.1007/978-3-031-04473-1.
Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Pühse, U. (2016). *Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. Psychophysiology*, *53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736.
Maliske, L.Z., Schurz, M., & Kanske, P. (2023). *Interactions within the social brain: Co-Activation and connectivity among networks enabling empathy and theory of mind. Neuroscience & Biobehavioral Reviews*, *147*, 105080. https://doi.org/10.1016/j.neubiorev.2023.105080.
Martin-Niedecken, A.L., Rogers, K., Turmo Vidal, L., Mekler, E.D., & Márquez Segura, E. (2019). ExerCube vs. personal trainer. In S., Brewster (Ed.), *Proceedings of the 2019 CHI conference on human factors in computing systems* (pp. 1–15). Association for Computing Machinery. https://doi.org/10.1145/3290605.3300318.
Martin-Niedecken, A.L., Segura, E.M., Rogers, K., Niedecken, S., & Vidal, L.T. (2019). *Towards socially immersive fitness games: An exploratory evaluation through embodied sketching. CHI play 2019 - extended abstracts of the annual symposium on computer-human interaction in play* (pp. 525–534). https://doi.org/10.1145/3341215.3356293.
Mcewan, D., & Beauchamp, M.R. (2014). *Teamwork in sport: A theoretical and integrative review. International Review of Sport and Exercise Psychology*, *7*(1), 229–250. https://doi.org/10.1080/1750984X.2014.932423.
McMorris, T., & Hale, B.J. (2012). *Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: A meta-analytical investigation. Brain and Cognition*, *80*(3), 338–351. https://doi.org/10.1016/j.bandc.2012.09.001.
Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). *The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734.
Moriguchi, Y. (2014). *The early development of executive function and its relation to social interaction: A brief review. Frontiers in Psychology*, *5*(388), 1–6. https://doi.org/10.3389/fpsyg.2014.00388.
Navarro, J., Quijano, S. D. De, & Berger, R. (2011). *Work-groups in organizations: A basic tool to manage increasing complexity and ambiguity. Papeles del Psicólogo, 32*(1), 17–28.
Nes, B.M., Janszky, I., Wisløff, U., Støylen, A., & Karlsen, T. (2013). *Age-predicted maximal heart rate in healthy subjects: The HUNT Fitness Study. Scandinavian Journal of Medicine & Science in Sports*, *23*(6), 697–704. https://doi.org/10.1111/j.1600-0838.2012.01445.x.
Perry, R.E., Braren, S.H., Rincón-Cortés, M., Brandes-Aitken, A.N., Chopra, D., Opendak, M., et al. (2019). *Enhancing executive functions through social interactions: Causal evidence using a cross-species model. Frontiers in Psychology*, *10*(2472), 1–11. https://doi.org/10.3389/fpsyg.2019.02472.
Pesce, C. (2012). *Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. Journal of Sport & Exercise Psychology*, *34*, 766–786. https://doi.org/10.1123/jsep.34.6.766.
Pesce, C., Ballester, R., & Benzing, V. (2021). *Giving physical activity and cognition research 'some soul': Focus on children and adolescents. European Journal of Human Movement*, *47*, 1–7. https://doi.org/10.21134/eurjhm.2021.47.1.
Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). *Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. Mental Health and Physical Activity*, *2*(1), 16–22. https://doi.org/10.1016/j.mhpa.2009.02.001.
Pesce, C., Vazou, S., Benzing, V., Álvarez-Bueno, C., Anzeneder, S., Mavilidi, M.F., et al. (2023). *Effects of chronic physical activity on cognition across the lifespan: A systematic meta-review of randomized controlled trials and realist synthesis of contextualized mechanisms. International Review of Sport and Exercise Psychology*, *16*(1), 722–760. https://doi.org/10.1080/1750984X.2021.1929404.
Pontifex, M.B., McGowan, A.L., Chandler, M.C., Gwizdala, K.L., Parks, A.C., Fenn, K., et al. (2019). *A primer on investigating the after effects of acute bouts of physical activity on cognition. Psychology of Sport and Exercise*, *40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015.
Redcay, E., & Schilbach, L. (2019). *Using second-person neuroscience to elucidate the mechanisms of social interaction. Nature Reviews Neuroscience*, *20*(8), 495–505. https://doi.org/10.1038/s41583-019-0179-4.
Schmeichel, B.J., & Tang, D. (2015). *Individual differences in executive functioning and their relationship to emotional processes and responses. Current Directions in Psychological Science*, *24*(2), 93–98. https://doi.org/10.1177/0963721414555178.
Schmidt, M., Benzing, V., & Kamer, M. (2016). *Classroom-based physical activity breaks and children's attention: Cognitive engagement works. Frontiers in Psychology*, *7*, 1–13. https://doi.org/10.3389/fpsyg.2016.01474.
Schulte, M., Trujillo, N., Villagra, O.A.R., Salas, N., & Ibañez, A. (2022). *The role of executive functions, social cognition and intelligence in predicting social adaptation of vulnerable populations. Scientific Reports*, *12*, e18693. https://doi.org/10.1038/s41598-022-21985-9.
Sebanz, N., & Bekkering, H. (2006). *Joint action: Bodies and minds moving together. Trends in Cognitive Sciences*, *10*(2), 70–76. https://doi.org/10.1016/j.tics.2005.12.009.
Smid, C.R., Karbach, J., & Steinbeis, N. (2020). *Toward a science of effective cognitive training. Current Directions in Psychological Science*, *29*(6), 531–537. https://doi.org/10.1177/0963721420951599.
Tomporowski, P.D., McCullick, B., Pendleton, D.M., & Pesce, C. (2015). *Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. Journal of Sport and Health Science*, *4*(1), 47–55. https://doi.org/10.1016/j.jshs.2014.09.003.
Tomporowski, P.D., & Pesce, C. (2019). *Exercise, sports, and performance arts benefit cognition via a common process. Psychological Bulletin*, *145*(9), 929–951. https://doi.org/10.1037/bul0000200.
Ybarra, O., Burnstein, E., Winkielman, P., Keller, M.C., Manis, M., Chan, E., et al. (2008). *Mental exercising through simple socializing: Social interaction promotes general cognitive functioning. Personality and Social Psychology Bulletin*, *34*(2), 248–259. https://doi.org/10.1177/0146167207310454.
Ybarra, O., & Winkielman, P. (2012). *On-line social interactions and executive functions. Frontiers in Human Neuroscience*, *6*, 1–22. https://doi.org/10.3389/fnhum.2012.00075.
Ybarra, O., Winkielman, P., Yeh, I., Burnstein, E., & Kavanagh, L. (2011). *Social psychological and personality science friends (and sometimes enemies) with cognitive benefits: What types of social interactions boost executive functioning? Social Psychological and Personality Science*, *2*(3), 253–261. https://doi.org/10.1177/1948550610386808.
Zelazo, P.D., Anderson, J.E., Richler, J., Wallner-Allen, K., Beaumont, J.L., Conway, K.P., et al. (2014). *NIH toolbox cognition battery (CB): Validation of executive function measures in adults. Journal of the International Neuropsychological Society*, *20*(6), 620–629. https://doi.org/10.1017/S1355617714000472.
Zelazo, P.D., & Carlson, S.M. (2012). *Hot and cool executive function in childhood and adolescence: Development and plasticity. Child Development Perspectives*, *6*(4), 354–360. https://doi.org/10.1111/j.1750-8606.2012.00246.x.