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Original Research

Effect of Intermittent Exercise on Performance in 3D Multiple Objects Tracking in Children, Young and Older Adults—A Pilot Study

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Abstract

Background: Although an extensive body of literature is trying to verify the acute effects of exercise, findings are highly contradictory due to many different study protocols. The number of studies using an intermittent exercise (IE) protocol is limited, especially with regard to comparison across the life span. We examined whether the effects of a HIIE protocol on performance in a perceptual-cognitive task (NeuroTracker® (NT)) differed between children, young adults, and older adults to address this gap. **Methods**: A total of 36 participants participated in the present study: 12 children (CH, 6 females, 9.83 $\pm$ 1.19 years), 12 young adults (YA, 6 females, 23.5 $\pm$ 3.55 years), and 12 older adults (OA, 4 females, 66.92 $\pm$ 4.08 years). The IE treadmill protocol used in the present study consisted of eleven 30-second intervals at 90% VO_2max, interspersed with 2-minute active recovery periods at 50% VO_2max. Before and during this exercise protocol, three series of the NeuroTracker® task were performed after 5, 15, and 25 minutes. **Results**: We observed a significant main effect time and a significant main effect group regarding absolute NT scores and progression during IE. YA had significantly higher absolute NT scores than CH and OA. The normalized perceptual-cognitive task progression was observed in OA and YA but not in CH. YA, in particular, showed progression in the NT performance during IE. **Conclusions**: The present study confirmed previous findings on age-related differences in NT performance. Based on these findings, the effects of different exercise protocols (e.g., continuous vs. intermittent) seem to be a worthwhile subject for future investigations. Normalized speed thresholds should best capture improvement differences between groups to compare results across studies better, as pre-test values are taken as the baseline.

Keywords: perceptual-cognitive performance; high-intensity interval exercise; acute exercise; neurotracker; executive function; multiple object tracking; dual-task

1. Introduction

Physical exercise positively impacts the body [1] and has several well-documented neurobiological effects, such as augmentations of brain vascularization and increases in proteins and neurotransmitters, which promote neurogenesis, neuronal survival, and angiogenesis overall brain volume enhancement [1,2]. High-intensity intermittent exercise (HIIE) has recently been shown to be an effective alternative to aerobic exercise programs, with positive effects on cognitive functions, such as information processing and response inhibition [3,4].

Although a substantial body of literature attempts to verify the acute effects of exercise on cognitive performance in children, young or older adults, findings are highly contradictory. For example, there are studies showing positive effects of exercise on cognitive performance [5–8], while other studies show a negative effect of exercise [9–13]. In addition, some studies demonstrated no effect of acute exercise (e.g., [13–15]) on cognitive performance. In terms of cognitive functions, acute exercise primarily improves executive functions (EF) that are associated with the prefrontal cortex, including attention, working memory, problem solving, cognitive flexibility, verbal fluency, decision making, and inhibitory control [16]. These positive changes have been shown to occur at very low to very high exercise intensities [17], with effects lasting up to two hours after exercise [18]. These effects depend on several factors, such as the exercise protocol (intensity and duration), the timing of cognitive testing (during versus post-exercise), the complexity of the tasks, and the fitness level of the participants [10,17,19]. Typically, acute effects of exercise are measured on a variety of simple cognitive tasks that target, for example, attention/perception (e.g., reaction time tests) or EFs such as working memory and inhibition (e.g., Flanker task, Stroop Color task, n-back task [20]). The consensus from the literature on acute exercise effects on cognitive performance is a small but positive effect of moderate HIIE, particularly in older adults [21–23]. However, Etnier *et al*. [24] noted that we are not dealing with a strong effect.

In general, all the exercises used in these studies increased heart rate, which may influence exercise-induced psychological arousal levels and play an important role in improving EF, possibly by increasing neural activity in the brain [10]. The mechanisms underlying the discussed effects of acute exercise on cognition are still under debate, and different neurophysiological explanations, such as the reticular-activating hypofrontality model [25] or the catecholamines hypothesis [26], emerged to explain these findings. However, there is evidence that the positive effects on cognition are caused by changes in the concentration of specific extracellular neurochemicals (neurotransmitters, neurotrophins, and neuromodulators; [27,28]). These neurotransmitters (e.g., dopamine, norepinephrine, serotonin, acetylcholine, GABA, and glutamate), neurotrophins such as brain-derived neurotrophic factor (BDNF), insulin-like growth factor-1 (IGF-1), and vascular endothelial growth factor (VEGF), and neuromodulators (e.g., endogenous opioids and endocannabinoids) in turn lead to increased plasticity along with altered synaptic transmission and induction of brain vascularization during physical exercises, particularly affecting prefrontal cortices, which are associated with thinking, decision making, and behavior (executive function hypothesis; [29,30]). Although increases in various neurochemicals have been confirmed, it is not entirely clear how these neurochemicals are involved in the changes in cognitive function induced by acute exercise [31]. For example, the effect of BDNF on plasticity or vascularization does not immediately lead to changes in cognitive performance. Instead, changes in the factors mentioned above are acute or chronic effects, which are changes that can occur as a result of exercise over a certain duration. Furthermore, vascular remodeling is not an acute process, nor is synaptogenesis. However, the modulation of a neurotransmitter or activation of its receptor on an endothelial cell, which causes vasodilation, are acute effects that may have an immediate impact on cognitive function.

There is a wide variation in the protocols used to deliver acute exercise intervention [32]. Most studies examining the effect of exercise on cognitive function focused primarily on continuous forms of exercise such as running or cycling at a constant intensity (low, moderate, and/or high). The number of studies using an intermittent exercise (IE) protocol is limited [33], although acute HIIE protocols tend to increase concentrations of certain extracellular neurochemicals more significantly than low-intensity acute exercise protocols in healthy young adults [31,34,35] and late- and middle-aged older adults [36]. In a prospective randomized controlled trial, Winter *et al.* [37] demonstrated that a HIIE protocol (2 $\times$ 3 min sprints) had greater benefits for cognition (vocabulary learning; exercise accelerates learning and improves long-term retention of learned material) than moderate-intensity exercise (40 min running) or a sedentary control condition in healthy male sports students. However, this study was conducted in fit adult participants, so its results must be applied with caution to younger and older people, as age and physical activity are moderating variables in the relationship between exercise and cognition ([16], see also Cooper *et al.* [29]).

The question remains whether or not the benefits of HIIE exercise on cognition, particularly EF, occur in children. Several studies demonstrated positive effects of HIIE on cognitive function in children [8,38–40]. Cooper *et al.* [38] stated that these findings in children are consistent with the literature for adults, suggesting that HIIE has a particularly positive effect on cognitive function. A recent systematic review summarized the existing evidence on the chronic effects of exercise interventions on cognitive function across the life span [41]. This review concluded that there is moderately strong evidence that moderate to high exercise intensities lead to improvements in cognition, especially processing speed, memory, and EF. According to this review article, the most substantial evidence is observed in children between 6 and 13 years and older adults over 50 years. Similar to this review, a meta-analysis by Chang *et al.* [17] investigating the effects of acute exercise on cognitive performance demonstrated that acute effects may have contributed to larger effects in children and older adults. Since these age groups are vulnerable to exercise, exercise's acute and chronic positive effects may be observed. However, the meta-analysis by Chang *et al.* [17] highlighted the difficulty in comparing the intensity and duration of acute physical activity due to different physiological developmental processes in children, young adults, and older adults. Overall, the results of this meta-analysis showed that moderate exercise had a positive effect on cognitive performance during and immediately after exercise and after exercise with a delay. Limitations in the experimental literature on children are that many of the studies have not described the experimental procedure of the exercise interventions (e.g., intensity) in sufficient detail, are often characterized by low methodological rigor, and show procedural differences that are likely due to the usual classroom-based research approaches to exercise and cognition in children (i.e., Tomborowski *et al.* [42]).

However, acute exercise is likely to affect complex cognitive tasks that engage the executive control system due to the interaction between executive tasks and brain function and exercise-induced stress [43]. The decline in performance is particularly evident during moderate-intensity [44] and high-intensity exercise [45]. Tasks that require EF are related to cognitive flexibility, inhibitory control, and working memory [32] and are more involved in prefrontal cortex functions than other simple tasks such as recall or short-term memory, visual search, or simple and choice reaction time [46]. Such simple tasks require focusing on identifying relevant stimuli and then responding to comparatively simple, predetermined responses [47] and show limited involvement in the function of the prefrontal cortex [48]. In contrast, multiple object tracking (MOT; [49]), in which multiple moving targets are tracked simultaneously, requires continuous task performance with higher-level cognitive functions. Also, MOT tasks resemble various everyday tasks that require tracking multiple objects, such as playing or watching various team sports, crossing a busy street, or driving in traffic. The Multiple Object Tracking (MOT) paradigm, first developed by Pylyshyn and Storm [49], has been used extensively to study MOT in a laboratory setting. Faubert and Sidebottom [50] introduced a perceptive-cognitive training program for athletes called NeuroTracker (NT; CogniSens Athletic, Inc., Montreal, Quebec, Canada). This training program is of great importance for processing information that requires attention and visual-spatial working memory in a dynamic context [50]. It stimulates many brain networks that must work together during exercise, including complex motion integration, dynamic, sustained, and distributed attention processing, dynamic visual-spatial processing, and working memory [51]. 3D-MOT tasks are now widely used in research to investigate dynamic visual attention in different groups of individuals (elderly, healthy controls, and children with neurodevelopmental disorders). For example, a recent study demonstrated a positive relationship between 3D-MOT ability and task performance in elderly participants tested with the NeuroTracker and two driving simulator scenarios. Better NeuroTracker performance was significantly associated with fewer crashes and lane deviations [52]. In another study, older participants performed worse than younger participants on MOT tasks [53]. Pothier *et al.* [54] tested MOT while walking simultaneously with young and older adults. They found a decrease in performance on the MOT with increasing complexity of the MOT task. An age-related decrease in MOT and walking performance was found, with older adults' performance impaired under conditions of high attentional load. Similar results were observed in children with neurodevelopmental disorders, in whom repeated 3D-MOT training resulted in better overall attentional performance on the Conners Continuous Performance Task [55].

In summary, much of the literature examining the exercise-cognition relationship focuses on young adults. However, there is a lack of information on children [56,57], especially compared with young and older adults. In addition, most studies measure cognitive performance at rest but rarely during exercise, and only few studies use HIIE protocols. Although our previous study investigated perceptual-cognitive performance using the NT during physical exercise in terms of a dual-task (DT) paradigm [58], studies examining this during acute exercise across the lifespan are still lacking. To address these gaps, we focus on the effect of a HIIE protocol on perceptual-cognitive performance during exercise in children (CH), young adults (YA), and older adults (OA). In a review by Basso and Suzuki [31], acute exercise was defined as a single bout of physical activity, such as the HIIT protocol used in this study. Therefore, we examine whether the effects of a HIIE protocol on performance in a perceptual-cognitive task differ between CH, YA, and OA. We expected that (1) all groups improve their perceptual-cognitive task performance throughout the HIIE protocol and that (2) YA, in particular, demonstrate better performance in the perceptual-cognitive task than OA and CH at rest and during exercise.

2 Materials and Methods

2.1 Study Design

This study employed a repeated-measures, within-subjects design.

2.2 Participants

Thirty-eight physically active participants participated in the present study: 12 children (8 to 12 years), 12 young adults (18 to 30 years), and 14 older adults (60+ years; see Table 1 (Ref. [59–61]) for group characteristics). This is based on a power analysis using G-power. We determined that a total sample size of at least 27 participants would suffice to detect between/within-factor interactions for repeated measures ANOVA, assuming a moderate effect size (f = 0.25) with alpha set at 0.05 and power at 0.8. Considering a 30% dropout rate, the sample was estimated to be 12 participants in each group, for a total of 36 participants. Recruitment occurred via a convenience-based, non-probability sampling approach (flyers at the University Sports Center and classroom announcement at a school in the Rhein-Neckar area containing the objectives and procedures of the experiment).

They were excluded if they reported (a) musculoskeletal disorders such as arthrosis affecting running, central or peripheral neurological diseases (e.g., previous stroke), (b) recent acute illness or surgery, (c) taking psychiatric drugs that may affect cognitive performance, and/or psychiatric disorders, (d) wearing glasses, as the use of 3D glasses was required. The following inclusion criteria were used to recruit participants: normal or corrected-to-normal vision and hearing, ability to walk independently, and the ability to follow instructions for testing. Two participants with preexisting myocardial conditions were excluded after an initial preliminary examination. Only healthy, active, and inactive participants were included.

The young and older adults were asked for their consent and willingness to participate in the study, and the children's legal guardian/next of kin provided written informed consent to participate in this study. The participants or the legal guardians of the children did not receive any financial compensation or incentive for taking part in the study. All assessments were conducted in accordance with ethical rules for research in human subjects following the Declaration of Helsinki [62].

Table 1. Sampling characteristics of children (CH), young adults (YA), and older adults (OA), including mean values (standard deviation) and statistical analyses of mean value differences.

	CH (n = 12)	YA (n = 12)	OA (n = 12)	stat. analyses
Age (years)	9.83 ± 1.19[b]	23.5 ± 3.55[a]	66.9 ± 4.08[a,b]	$F(2, 33) = 1042^{***}$, $\eta_p^2 = 0.984$
Sex (n male)	6	6	8	$\chi^2(2) = 0.900^{ns}$
Education (years)	3.83 ± 1.19[b]	14.4 ± 0.79	13.1 ± 3.58[a]	$F(2, 33) = 80.5^{***}$, $\eta_p^2 = 0.835$
Weight (kg)	34.1 ± 6.81	68.2 ± 9.75[a]	70.9 ± 9.02[a,b]	$F(2, 33) = 67.9^{***}$, $\eta_p^2 = 0.805$
Height (cm)	1.48 ± 0.12	1.76 ± 0.72[a]	1.73 ± 0.06[a,b]	$F(2, 33) = 38.5^{***}$, $\eta_p^2 = 0.700$
BMI (kg/m^2)	15.5 ± 1.65	21.9 ± 1.54[a]	23.5 ± 1.92[a]	$F(2, 33) = 74.8^{***}$, $\eta_p^2 = 0.819$
HRmax[#] (beats/min)	201 ± 8.35[b]	186 ± 6.64[a]	161 ± 2.85[a,b]	$F(2, 33) = 277^{***}$, $\eta_p^2 = 0.944$
Sports activity/week (min)	279 ± 155	323 ± 295	215 ± 81	$F(2, 33) = .891^{ns}$, $\eta_p^2 = 0.051$
Bruce protocol[§] (min)	8.90 ± 1.83[b]	13.2 ± 1.87[a]	5.60 ± 1.76[a,b]	$F(2, 33) = 51.9^{***}$, $\eta_p^2 = 0.759$
VO_2max* (mL/kg/min)	33.3 ± 5.55[b]	49.9 ± 5.99[a]	20.6 ± 5.55[a,b]	$F(2, 33) = 74.0^{***}$, $\eta_p^2 = 0.818$
MoCA	n.a.	n.a.	29.6 ± 1.38	n.a.

Note: $^{***}p < 0.001$; $^{*}p < 0.05$, ns, not significant; n.a., not available; [a] significant different from CH ($p < 0.001$); [b] significant different from YA ($p < 0.001$); [#] The maximum heart rate (HRmax) were performed for all participants depending on age: HRmax = 208 – (0.7 × age) [59], Maximal oxygen uptake (VO_2max) was estimated by sex using the following formulas over duration (factor T) from the Bruce protocol: $VO_2max = 14.8 - (1.379 \times T) + (0.451 \times T^2) - (0.012 \times T^3)$ for males (Foster *et al.* [60]) and $VO_2max = (4.38 \times T) - 3.9$ for females (Pollock *et al.* [61]). [§] Time to termination in the submaximal Bruce protocol.

2.3 Measures

2.3.1 Demographic Information, Physical Activity, and Cognitive Status

Participants' demographic information was collected, their height and weight were measured, and the body mass index (BMI, kg/m^2) was calculated.

We used a questionnaire validated in our laboratory [63,64]. It records the types of sports and the frequency of weekly sports activity (frequency/week and duration/exercise session) with the following questions: What sports do you do in the club (or recreational). How many training sessions do you currently complete per week in the club? How long does a training session last on average? Then, the total sports participation (h/week) was calculated as follows: (frequency_activity1 × duration_activity1) + (frequency_activity2 × duration_activity2) + (frequency_activity3 × duration_activity3). The different sports (e.g., team sports such as soccer, handball, basketball, individual sports such as gymnastics, boxing, or endurance sports such as swimming, cycling, track and field) were heterogeneous between participants. Therefore, they were not considered in the further analysis also due to the small number of cases. Mild cognitive impairment (MCI) was only assessed in OA using the Montreal Cognitive Assessment (MoCA; [65]). The MoCA score was used to participate in the experiment in older adults without cognitive decline (above 26 scores).

2.3.2 Maximum Oxygen Uptake (VO_2max)

In the present study, the Bruce protocol [66] was performed on a treadmill (model: h/p/cosmos pulsar® 3p, Nussdorf-Traunstein, Germany) to determine the maximum oxygen uptake (VO_2max), which is considered to be a decisive parameter of endurance performance [67]. The Bruce protocol starts with an initial speed of 2.7 km/h and an incline of 10%. Every 3 minutes, the incline increases by 2% and the speed by 1.3 km/h per stage (see **Supplementary Fig. 1**). The heart rate was recorded throughout the test (Polar H1 Heart Rate Sensor, Polar Electro Europe AG, Switzerland), and the participant's subjective exertion was recorded at the end of each stage using the Borg scale (Scale from 6–20; [68]). The criteria for termination were submaximal. The protocol was terminated at 85% of the maximum heart rate (HRmax = 208 – (0.7 × age) (beats/min); Tanaka *et al.* [59]), a value of 17 on the Borg scale or voluntary withdrawal. All participants were attached to a harness during the Bruce protocol (H/P/cosmos) for fall prevention.

2.3.3 Perceptual-Cognitive Performance Task

The 3D-MOT (3D Multiple Object Tracking) is a perceptual-cognitive training program under the NeuroTracker® system licensed by the University of Montreal (NT; CogniSens Athletic, Inc., Montreal, Quebec, Canada). The participants stood or ran on a treadmill with 3D glasses; their position was chosen to move at an angle of 45 degrees in front of a 3D TV (Samsung, 65 inches).

To complete the task, participants must track the target objects in Core mode while ignoring the distraction objects. At the beginning, participants are presented with eight yellow balls for 2 seconds, four of which briefly light up orange to signal which balls they must track. Then, all eight balls return to their original yellow color and move in the 3D space across the screen for eight seconds. Next, participants track the four target balls as all balls move while

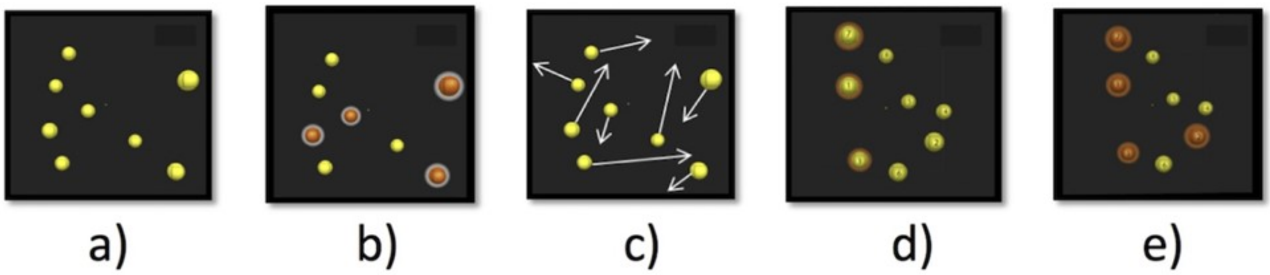

Fig. 1. 3D-MOT task. (a) Presentation of the randomly positioned objects in a virtual volumetric space. (b) Target objects to be tracked during the trial. (c) Movement of all objects with dynamic interactions. (d) Observer's response by identifying the target objects. (e) Feedback is given to the observer (with permission from the author; [70]).

ignoring the four distraction balls. Once all eight balls stop moving, participants select the four balls they think are the target balls by naming the corresponding numbers. If the participant correctly identifies all four target balls, the speed of the next trial increases. However, if the participant does not correctly identify all four balls, the speed of the next trial decreases. In this way, a session-specific speed threshold is calculated (staircase method; [69])), which is then used as the average visual pursuit speed (achieved speed (cm/s) after 20 repetitions; NT score). Both the score and the hit rate (proportion of target balls correctly identified) of each session are included in the analysis. The individual phases of the task are shown in Fig. 1 (Ref. [70]). Each session lasted between six and eight minutes. The NT score has proven to be a valid indicator of high-brain cognitive function [51,71].

2.4 Acute Exercise — High Intermittent Exercise Treadmill Protocol

The HIIE treadmill protocol used in the present study consisted of eleven 30-second intervals at 90% VO_2max, interspersed with 2-minute active recovery periods at 50% VO_2max (see **Supplementary Fig. 2**). Based on the estimated maximum oxygen uptake, an individualized, approximately 35-minute HIIE program was created for each participant. During this exercise protocol, three series of the NeuroTracker® task were performed after 5, 15, and 25 minutes (see **Supplementary Fig. 2**). Participants were again attached to a harness for safety reasons and were informed of the subsequent change in intensity at the end of each interval.

2.5 Experimental Setup and Procedure

All measures were conducted in the Institute for Sports and Movement Science laboratory at the University of Stuttgart. The overall test procedure per participant comprised two test dates, each lasting 90 minutes, two weeks apart. On the first day of testing, participants (in the case of children and their legal guardians) were informed about the purpose of the study and signed an informed consent form. A questionnaire was used to collect demographic information and sports biography. The MoCA was used to screen older adults for cognitive impairment. After 15 minutes of rest, perceptual-cognitive performance was assessed with the NeuroTracker® software (baseline1: one session with 20 trials) while standing, followed by assessing aerobic endurance on a treadmill using the Bruce protocol. On the second day of testing (2 weeks later), the perceptual-cognitive task was again performed while standing (baseline2: one session with 20 trials) and during the HIIE protocol (HIIE condition: three sessions with 20 trials each at HIIE-5 min, HIIE-15 min, and HIIE-25 min). All measures on the first and second day of testing were conducted in the morning (see Fig. 2).

2.6 Statistical Analysis

Data were analyzed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). First, we explored all dependent variables to examine missing values, normality of distributions as a prerequisite for calculating the ANOVAs (tested by Kolmogorov–Smirnov tests), and the presence of outliers. An alpha level of 0.05 was used for all statistical tests. Group comparison with respect to the three age groups was analyzed for continuous variables (age, BMI) using repeated measures ANOVAs, and sex as categorical demographic variables was analyzed using the Chi-Square test.

The course of perceptual-cognitive tasks (speed threshold) was analyzed using both absolute (unprocessed speed thresholds) and normalized values (processed speed thresholds; [55]). Normalized values represent performance relative to the mean of baseline1. Thus, in terms of normalized progressions, baseline1 is the zero value, and improvements/declines at subsequent time points (baseline2, HIIE-5 min, HIIE-15 min, and HIIE-25 min) vary based on participants' performance at baseline1. We divided the data obtained in each session (baseline1, baseline2, HIIE-5 min, HIIE-15 min, and HIIE-25 min) by the data obtained in baseline1 to calculate changes in the progression.

Each possible predictor variable was first mean-centered, where each individual score was subtracted from the average value to determine the correlations between

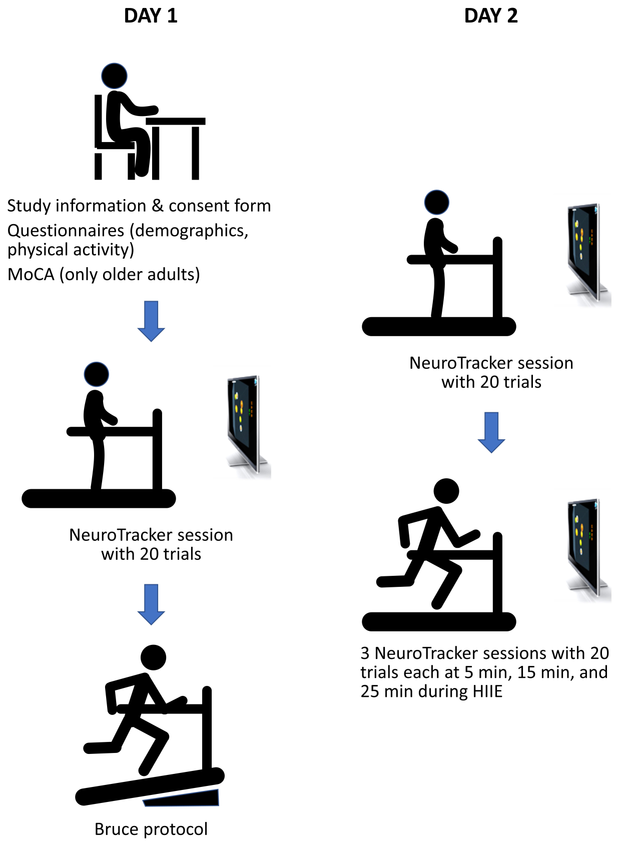

Fig. 2. The experimental design of this study.

NT performance and age, BMI, education, exercise, and VO_2max. This was done so that the variables could be compared on a similar, continuous scale. Next, the mean-centered values were entered into a Pearson bivariate correlation. Significant predictor variables were used as covariates for the ANCOVAs with repeated measures.

A 3 (group: CH, YA, and OA) × 5 (time: baseline1, baseline2, HIIE-5 min, HIIE-15 min, and HIIE-25 min) ANCOVA with repeated measurement was performed in order to detect a difference between the groups in the absolute performance of the perceptual-cognitive tasks (unprocessed speed thresholds) controlled for VO_2max. A 3 (group: CH, YA, and OA) × 3 (time: HIIE-5 min, HIIE-15 min, and HIIE-25 min) ANCOVA with repeated measurement controlled for VO_2max was conducted to examine group differences in the absolute perceptual-cognitive task performance (unprocessed speed thresholds) during HIIE (dual-task). A 3 (group: CH, YA, and OA) × 5 (time: baseline1, baseline2, HIIE-5 min, HIIE-15 min, and HIIE-25 min) ANCOVA with repeated measurement controlled for VO_2max was calculated to show group differences in the progression of perceptual-cognitive performance in ratio to baseline1 (normalized speed thresholds).

If the result of the ANOVAs were significant, post-hoc tests (Bonferroni correction) were used to test which factor levels (group) were significantly different from each other. Effect sizes for all ANOVAs were expressed using the partial Eta^2 (η_p^2; conventions of Cohen [72]: 0.01 small effect; 0.06 medium effect; 0.14 strong effect).

3. Results

3.1 Participants

Table 1 shows the characteristics of the sample. All participants can be classified as normal-weighted according to the current WHO criteria. On average, adults have a high level of education. None of the older adults had a MoCA score that would categorize them as cognitively impaired. Fitness is at least adequate in all participants as measured by VO_2max. YA show a significantly higher endurance capacity (VO_2max) than CH and OA. In addition, YA can perform the Bruce protocol for more than twice as long as OA. The physical activity level and the VO_2max show an active and fit sample overall.

3.2 Correlations between NT Performance and the Predictor Variables Age, BMI, Exercise, and VO_2max

There were no significant correlations between NT performance and BMI and the weekly sports activity. However, moderate correlations were found for NT performance and VO_2max in children and younger adults but not in older adults (see Table 2). Based on these results, only VO_2max was further considered a covariate in subsequent analyses.

3.3 Absolute and Normalized Perceptual-Cognitive Task Progression

Repeated measures ANCOVA for absolute NT scores controlled for VO_2max showed a significant main effect time, $F(4, 128) = 12.8$, $p < 0.001$, $\eta_p^2 = 0.285$ and a significant main effect age group, $F(2, 32) = 4.14$, $p = 0.025$, $\eta_p^2 = 0.205$ (Fig. 3). Post-hoc pairwise comparisons showed that YA ($M = 1.70$, $SE = 0.20$) had a higher NT score than CH ($M = 1.17$, $SE = 0.11$, $p = 0.096$) and OA ($M = 0.69$, $SE = 0.19$, $p = 0.022$). CH also differed from OA ($p = 0.074$). The interactions time × group, $F(8, 128) = 0.81$, $p = 0.598$, $\eta_p^2 = 0.048$, is not significant. The interaction time × VO_2max was also not significant, $F(4, 128) = 0.12$, $p = 0.975$, $\eta_p^2 = 0.004$.

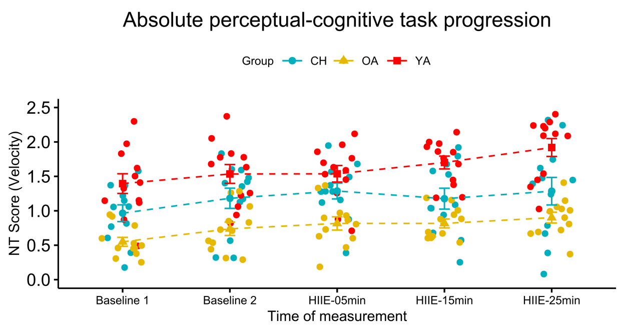

Fig. 3. Absolute perceptual-cognitive task progression.

Table 2. Pearson correlations for NT performance and the mean-centered predictor variables separated by children (CH), young adults (YA), and older adults (OA).

	NT performance				
	Baseline1	Baseline2	HIIE-5 min	HIIE-15 min	HIIE-25 min
			Children		
BMI	0.393	0.366	–0.087	0.096	0.086
Sports activity/week	0.342	0.176	0.282	0.365	0.095
VO_2max	–0.590*	–0.501	–0.441	–0.628*	–0.507
Education	0.529	0.453	0.672*	0.491	0.745*
			Young adults		
BMI	0.039	0.005	0.121	0.321	0.384
Sports activity/week	–0.122	–0.019	0.154	0.082	0.302
VO_2max	0.360	0.485	0.352	0.543	0.656*
Education	0.186	0.108	–0.263	–0.426	–0.292
			Older adults		
BMI	0.124	–0.278	0.124	0.155	–0.213
Sports activity/week	0.215	–0.092	–0.055	0.176	–0.294
VO_2max	0.011	–0.014	0.051	0.213	0.002
Education	–0.415	–0.073	–0.284	0.153	–0.395

Note: $*p < 0.05$.

Regarding progression during HIIE, we saw a significant main effect time, $F(2, 64) = 6.12$, $p = 0.004$, ${\eta_p}^2 = 0.161$, and a significant main effect group, $F(2, 32) = 3.80$, $p = 0.033$, ${\eta_p}^2 = 0.192$. NT scores increased with the duration of exercise (HIIE-5 min: $M = 1.21$, $SD = 0.065$; HIIE-15 min: $M = 1.23$, $SD = 0.064$; HIIE-25 min: $M = 1.37$, $SD = 0.085$). In addition, the time × group interaction approached significance, $F(4, 64) = 1.99$, $p = 0.10$, ${\eta_p}^2 = 0.11$ during HIIE (Fig. 4). In particular, YA show performance improvements in the perceptual-cognitive task during HIIE (HIIE-5 min: $M = 1.57$, $SE = 0.208$; HIIE-15 min: $M = 1.84$, $SD = 0.204$; HIIE-25 min: $M = 2.01$, SD = 0.272. CH and OA remained constant in their performance.

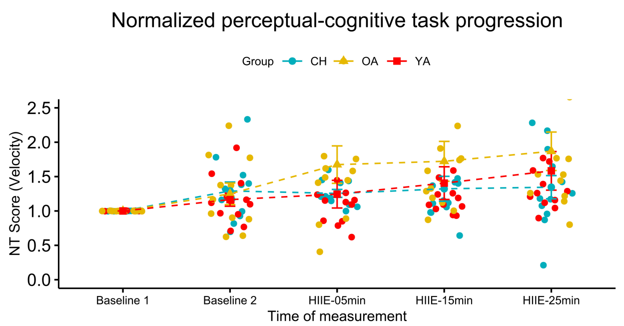

Fig. 4. Normalized perceptual-cognitive task progression.

Repeated measurement ANCOVA for normalized NT scores controlled for VO_2max showed a significant main effect time, $F(2.36, 70.9) = 7.59$, $p = 0.001$, ${\eta_p}^2 = 0.202$. The main effect group was not significant, $F(2, 30) = 0.48$, $p = 0.625$, ${\eta_p}^2 = 0.031$. The interactions time × group, $F(4.73, 70.9) = 0.76$, $p = 0.575$, ${\eta_p}^2 = 0.048$ and time × VO_2max, $F(2.36, 70.9) = 0.09$, $p = 0.940$, ${\eta_p}^2 = 0.003$ were not significant. However, we saw greater improvements in the perceptual-cognitive task performance in YA and OA compared to CH. There was a significant linear trend in the within-subjects factor (time) for OA ($p = 0.004$), but not for YA ($p = 0.076$) or CH ($p = 0.175$).

4. Discussion

This study aimed to examine the performance of CH, YA, and OA on a perceptual-cognitive task during an HIIE. Considering baseline measures, the group of YA performed best and achieved significantly higher absolute NT scores than CH and OA.

Legault *et al*. [63] reported similar results on young and older adults in a previous study. This pattern is also consistent with Kennedy *et al*. [73], who observed an age-related decline in tracking ability and suggested that these findings may indicate a decline in higher-level cognitive functions. In addition, Trick *et al*. [74] noted that, on average, YA could track four targets at once, whereas OA can track around three targets (see also Alvarez and Franconeri [75]). These results may be related to the development of functions thought to be involved in MOT, mainly working memory [76] and attention [77,78]. In MOT tasks, participants must continuously monitor (i.e., track) the changing spatial positions of targets and actively maintain target representations over time, which requires visual working memory, another process involved in MOT. Drew *et al*. [79] showed neural activity, indicating that two separate mechanisms are involved in tracking: an indexing mechanism closely associated with visual working memory and a mechanism that tracks target locations. There appears to be a high degree of inter-individual variability in this tracking threshold, which may link to MOT expertise. For example, the ability of humans to track multiple objects simultaneously increases with age [80]. Various examples from daily life include monitoring children on a playground or in a swimming pool, tracking multiple vehicles and pedestrians while driving, or watching a soccer match. Oksama and Hyönä [81] examined individual differences in MOT performance and found that visual-spatial short-term memory capacity of 2 to 6 items was a significant predictor of MOT, indicating a role for memory in tracking. The well-documented performance limitations (e.g., speed, distances, number of targets) also suggest that a limited attentional resource is available to support tracking. In particular, increasing the difficulty of a MOT task can deplete the attentional resource to the point where a second object cannot be tracked [82].

Since both attention and working memory can be affected by age, it seems reasonable to expect age-related decrements in performance on MOT tasks [83]. Furthermore, the significant difference between CH and YA and OA in the present study is consistent with previous examinations of MOT performance in childhood and across the lifespan [53,74]. Moreover, Trick *et al*. [74] and Harris *et al*. [84] suggest that regular exposure to certain real-life activities, such as action sports and videogames, is associated with higher MOT performance. Therefore, CH likely performs better than OA because they experience such gaming situations and complex dynamic scenes more frequently in their everyday lives. However, Legault *et al*. [85] pointed out that further experiments will be required to identify which functions may be affected by aging since 3D-MOT is a complex task sensitive to many factors.

Considering NT performance during HIIE, the present study includes DT conditions (i.e., running while MOT) that target participants' ability to flexibly allocate attentional resources and switch between the goals of the tasks performed in parallel (cognitive flexibility). There is strong evidence that OA demonstrate greater DT costs than YA [54,86] as they require more time to switch between two different tasks [87]. Thus, these decreases with increasing age and demands of the NT could explain the differences in the absolute task progression between YA and OA. The reticular-activating hypofrontality model (RAH; [48,88]) hypothesizes that acute exercise shifts the brain's metabolic resources away from specific regions such as the prefrontal cortex and instead favors structures that support exercise, such as the reticular formation and motor cortices. This process would facilitate sensory and motor task performances, whereas the associated hypofrontality would impair EF. Therefore, the effects of shifting metabolic resources can be greater in OA than CH, resulting in less MOT task progression, particularly in OA. The significant improvement in absolute NT scores in YA during HIIE seems consistent with the notion that acute exercise has a small positive effect on cognitive performance [5,7]. Notably, since performance in CH and OA remains relatively constant, this may be indicative of age-related differences in potential effects of acute HIIE.

However, the present findings are inconsistent with learning effects in MOT tasks, as previous studies demonstrated continuous task progression in different populations [89], including YA and OA adults [85], concluding that both have a similar ability to improve with training. In the absence of a significant interaction time $\times$ group on NT scores normalized to baseline performance, the present results diverge further with respect to group differences in task progression. This may be related to the wide variability in study designs, experimental and stimulus characteristics, and statistical analyses, which are limitations of research investigating MOT during exercise. The NeuroTracker® must be further tested in terms of its psychometric properties (see Vater *et al*. [89]). Studies may also be biased by other moderating factors, such as the type, duration and intensity of exercise, physical fitness, and timing and type of cognitive tasks assessed [10,17,19,33]. However, no significant effects of aerobic endurance performance on NT performance were found in our study. Also, this study does not address whether the changes observed in this study are due to training at all or whether they are simply to be expected due to the natural cognitive function that occurs throughout life. However, learning effects seem to have similar albeit different trajectories in CH, YA, and OA, with greater improvements in YA and OA. It is not appropriate to speak of comparison across the life span because of the absence of a middle-aged adult group. In fact, the choices and lifestyle in these middle years likely have the greatest impact on brain health (including cognitive performance) in old age [90].

5. Conclusions

In conclusion, the present study confirms previous findings on age-related differences in NT performance. Results show that YA perform better than CH and OA at baseline and during HIIE. However, in all three groups, we saw an improvement in NT performance for the absolute scores. Beneficial effects of acute HIIE on perceptual-cognitive performance may be confounded with learning effects and cannot be inferred from mere task progression; therefore, future studies should include a control group without HIIE but with perceptual-cognitive training. Based on the present findings, the effects of different exercise protocols (e.g., continuous vs. intermittent) seem to be a worthwhile subject for future investigations. Normalized speed thresholds should best capture improvement differences between groups to compare results across studies better, as pre-test values are taken as the baseline.

Abbreviations

CH, children; HIIE, high-intensity intermittent; exercise; IE, intermittent exercise; MOT, multiple object tracking; NT, NeuroTracker; OA, old adults; YA, young adults.

Author Contributions

TJK—Formal analysis, Writing-Original draft, Visualization; SYP—Conceptualization, Methodology, Investigation, Data Curation, Writing-Original draft; VB—Investigation, Writing-Reviewing and Editing; NS—Conceptualization, Methodology, Writing-Reviewing and Editing, Visualization, Supervision.

Ethics Approval and Consent to Participate

The study was conducted according to the guidelines of the Declaration of Helsinki. After consultation of the Ethics Committee of the University Stuttgart, the anonymous analysis of data of our participants, which were collected as part of intervention, needed no guidance after the Professional Code for Physicians in Germany (§15 (1)). There were no concerns of the commission about collecting, processing and publishing such data. Also, regarding the guidelines of the German Research Foundation (DFG), no ethics application was required to conduct this study. All younger and older adults and the children and their parents/caregivers gave their written informed consent.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/j.jin2104122.

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