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Article type : Original Article

The Effect of Exergaming on Executive Functions in Children with ADHD: A Randomized Clinical Trial

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Running head: Exergaming and ADHD

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/sms.13446

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Abstract

Background: Children with ADHD frequently suffer from deficits in cognitive (i.e. executive functions) and motor abilities. Although medication usually has a positive effect, a lack of commitment and possible side effects result in a need for adjunct or alternative treatments. Thus, the aim of the current study was to investigate the effects of cognitively and physically demanding exergaming on executive functions, ADHD symptoms and motor abilities.

Methods: In a parallel group randomized trial, 51 children between 8-12 years ($M = 10.63$; $SD = 1.32$) diagnosed with ADHD were assigned either to an 8-week exergame intervention group (three training sessions per week for 30 min), or a waiting-list control group. The core executive functions (inhibition, switching, updating), parent ratings of symptoms, and motor abilities were assessed/gathered before and after the intervention.

Results: Analyses of covariance (using pre-test values as covariates) revealed that children in the exergame intervention group improved in specific executive functions (reaction times in inhibition and switching), general psychopathology as well as motor abilities compared to control group.

Conclusions: Findings indicate that exergaming might benefit two domains in which frequent deficits can be observed in children with ADHD; executive functions and motor abilities. Given that these beneficial effects in turn might positively affect psychopathology, exergaming could serve as an individualized home-based intervention in the future. However, in order to maximize benefits and make exergaming a valuable adjunct to treatment for children with ADHD, customized exergames are needed.

Clinical trial number: KEK 393/15; DRKS00010171; <http://www.drks.de/DRKS00010171>

Keywords: Attention Deficit Hyperactivity Disorder; active video gaming; exercise; cognition, cognitive performance, ADHD symptoms, symptoms, motor abilities

Introduction

Attention deficit hyperactivity disorder (ADHD) is one of the most common neurodevelopmental disorders in childhood and adolescence, with a prevalence of 3-7% ¹. The disorder can have a great impact on affected individuals, their families, as well as on society ². For example, the disorder is linked to low school performance and poor long-term academic achievement in childhood ³. Furthermore, over half of the children diagnosed with ADHD show difficulties in gross and fine motor skills ⁴ and developmental coordination disorder is a frequent comorbidity of ADHD ⁵.

The key symptoms of ADHD include inattention and/ or hyperactivity-impulsivity. This pattern of symptoms frequently interferes with functioning and/or development, persists over time and typically manifests itself in childhood ⁶. According to the DSM-5, the disorder can be further specified in a predominantly inattentive, hyperactive/impulsive or combined presentation ⁶. These symptoms are frequently linked to reduced executive function (EF) performance ^{7,8}. Although deficits in EFs can be reduced through medication, issues such as potential side effects, low compliance and unknown long-term consequences call for alternatives in treating EF deficits.

EFs are higher-order cognitive functions that modulate fundamental cognitive processes and therefore are required for goal-oriented, adaptive and flexible behavior ⁹. EFs are thought to be comprised of three core processes: *inhibition*, which includes inhibiting predominant responses and controlling attention; *switching*, which includes switching between tasks or mental sets; and *updating*, which includes retaining information and processing it. All three core EFs are highly relevant to learning and consequently to academic achievement in children with ADHD ^{9,10}.

Whereas in healthy children there is substantial evidence showing that physical exercise has a positive effect on EFs ^{11,12}, there are fewer studies addressing the impact of exercise interventions in children with ADHD. There is, however, a growing body of evidence available for interventional studies in children with ADHD, indicating that this population might also benefit from physical exercise, positively impacting cognitive performance, ADHD symptoms and motor abilities ^{13,14}. Therefore, physical exercise is suggested to be a promising alternative or additional treatment option ¹⁴.

Several neurobiological, psychosocial and behavioral mechanisms have been proposed to explain the effects of physical activity on mental health¹⁵. For example, in the behavioral hypothesis it is assumed that sleep patterns, self-regulation and coping skills are improved through regular physical activity. This seems highly relevant for children with ADHD, because quality of sleep is frequently impaired in these individuals, and has been found to be associated with cognitive performance as well as cognitive and behavioral problems^{16,17}.

In the neurobiological hypothesis, it is assumed that physical activity at a moderate-to-vigorous intensity induces catecholamine neurotransmission, neurogenesis/angiogenesis and neuroplasticity¹⁸. In children with ADHD, it is supposed that these modulations occur especially in the brain areas which underlie symptomatology. Therefore, disrupted neurotransmission mechanisms and brain alterations might improve particularly in this population¹⁹. Nevertheless, several different physical activities with varying intensities were used in the small number of previous studies²⁰.

Not only quantitative (intensity and duration), but also qualitative characteristics are proposed to be crucial for EF benefits^{21,22}. In the cognitive stimulation hypothesis, it is assumed that modality, i.e. cognitively engaging physical exercise, leads to increased benefits for cognitive performance through training the same brain regions that are used to control higher order cognition^{21,23,24}. For example, in a recent study it was shown that a 6-week intervention of cognitively demanding team games, but not a pure aerobic exercise intervention, had a positive effect on primary school children's EFs²⁵. Similarly, in children with ADHD, there seems to be evidence that mixed physical exercises (including multiple activities) might have the greatest potential to improve ADHD symptoms²⁶. Furthermore, this was highlighted in an influential review indicating that activities including physical and cognitive challenges might serve as treatment for ADHD¹⁹. Along similar lines, Moreau and Conway²⁷ recommend a combined physical and cognitive training program in order to have the largest effect on children's EFs. From an applied perspective, however, the question arises as to what exactly a program should look like that is both cognitively and physically demanding, and moreover, suitable for children with ADHD.

A combination of physical and cognitive training can be achieved through “exergaming”. Exergaming is a portmanteau of “exercise” and “gaming”, and refers to digital games that require bodily movements to play, stimulating an active gaming experience to function as a form of physical activity ²⁸. As a result of motivational problems and a lower level of positive reinforcement, children with ADHD often find traditional (cognitive) training programs uninteresting and tiring ²⁹. Exergaming helps to combine physical and cognitive training in a gamified fashion, ensuring motivation, diversity and adaptivity. Initial investigations have yielded promising results and suggest that exergaming could serve as an intervention for promoting health-related outcomes and EFs ³⁰.

The potential of a home-based exergaming intervention for counteracting the cognitive and motor deficits of children affected with ADHD is particularly relevant when considering that they frequently drop out of traditional sports programs ³¹, and spend about twice as much time (daily ~ 6 hours) sedentary in front of a TV or computer screen ³². Since sedentary (screen) time is not only harmful for children’s physical health, but also a risk factor for ADHD symptom severity ³³, new methods to decrease sedentary time and subsequently benefit cognitive functions are needed. An exergaming intervention that would replace sedentary screen time and promote positive effects could be easily distributed and is highly scalable.

Therefore, the aim of this study was to investigate the effects of an exergame intervention (characterized by both physical and cognitive demands) on the core EFs in children with ADHD. Based on reviews indicating that physical activities which include physical and cognitive demands have larger benefits for executive functions ^{11,22,34}, for the primary outcome, we hypothesized that children in the exergame group would perform better in the three core EFs (inhibition, switching and updating) than the waiting-list control group. Based on reviews indicating that physical activity has a positive effect on ADHD symptoms and motor abilities ^{19,20,26}, for secondary outcomes, we expected positive effects on these domains in the exergaming condition compared to the waiting-list control group.

Material and methods

Design and Procedures. This clinical trial (for CONSORT checklist see Table S3, available online) was conducted in the canton of Bern, Switzerland. It was granted ethical approval by the ethics committee of the canton of Bern, Switzerland (KEK-NR. 393/15) and was registered with the German (WHO) Register of Clinical Trials (DRKS00010171). The legal guardians of all participants provided written informed consent and children provided assent to participate. Using a parallel pre-post study design, children were randomly (and concealed) assigned to an experimental or a waiting-list control group by the principle investigator (using randomizer.org; for study protocol see ³⁵). Participants were blinded with regard to study aims. Following randomization, the exergame training was set up at the participant's home, and a first supervised training session was conducted. EFs were assessed prior to (pre-test) and following (post-test) the 8-week period of intervention or control. Both assessments took place in a quiet room at the respective family's home, to make participating in the study as convenient as possible. Testing was scheduled between 1 p.m. and 4 p.m. in both groups. During the intervention, participants filled out training diaries, in which they had to report the training duration and their valence after each single session. After completing the post-test, the participants received a small gift, and the purpose of the experiment was explained to the participants and parents.

Participants. Any child between the ages of 8 and 12 years, who had been previously diagnosed with the ADHD by a medical professional based upon the International Statistical Classification of Diseases and Related Health Problems (ICD-10) ³⁶, was eligible to take part in the study. For safety reasons, people suffering from a neurological disorder, Tourette syndrome or an epileptic disorder were excluded from the study. In total, 51 participants (ages 8-12 years) were recruited through an association for parents and caregivers of children and adults with ADHD (see Table 1). The participating children were on average 10.43 years old ($SD = 1.37$) and 82.4% of them were boys. During the time of the study, they were all attending regular schools and their socioeconomic status

was comparable to a previous study in school children ²⁵. Overall, children's ADHD symptoms (inattention, hyperactivity, combined) can be categorized as borderline to clinically elevated and their general psychopathology, which comprises other mental health problems in addition to ADHD symptoms, was found to be clinically elevated. In motor abilities, 37.2% of the participating children were considered as below average compared to age related norm values.

Seven participants dropped out during the study (see Figure S1, available online). Six participants in the exergaming group indicated that they were not able to keep up with the training and refused to participate in the post-test. In addition, one participant from the control group was unwilling to participate in the post-test. To provide an intention-to-treat analysis and include all participants, the post-test data of the missing seven participants was augmented using multiple imputation (five datasets) with full conditional specification (Markov chain Monte Carlo method). Compared to single imputation, in multiple imputation, several data sets are generated in which the missing values are imputed based on all the other variables of the same dataset ³⁷. Standard errors can be calculated using Rubin's rules, which take into account the variability in results between the imputed datasets. The pattern of results did not change when the same analyses were conducted without imputed data.

According to the initial study protocol, a total sample size of 66 participants and a third measurement point was planned. Since we did not reach more children through the parents and caregivers association, and the received funding covered only the inclusion of these children as well the assessment of two measurement points, this clinical trial included 51 participants. Nevertheless, power calculation using G*Power revealed 44 participants as the minimal sample size for a general model with repeated measures (1 – beta error probability = .80; alpha error probability = .05; small to medium effect size $f = .14$; number of groups = 2, number of measurements = 2; correlation between the repeated measures $r = .80$).

Intervention. The exergaming intervention was compared to a waiting-list control group. The exergaming intervention was carried out using the Xbox Kinect (Microsoft, Redmond, WA). This is a game console including a motion-sensing input device. Users control and interact with the console through their body movements. The user is projected directly into the virtual reality on the screen by integrated cameras.

The first exergaming session was conducted under the supervision of specifically trained research assistants. The parents were asked to assist and support the children with the training. Children agreed to train for 8 weeks (3 times a week for at least 30 min) with “Shape UP” (Ubisoft, Montreal, Canada), and adherence was indirectly assessed from children’s diaries. The game is designed to be adaptive, automatically adjusting to the player’s level of proficiency. In this exergame, the physical activity is conducted playfully. The performance of each session is recorded by the computer and the child can compete against their own “high score” (records of old performances) in order to improve. This ensures a continuous adaptation to the corresponding level of performance with regard to physical and cognitive challenge. Within the game, there are six different “workouts” to play.

One example for a workout is the “Beatmaster Training Quest”: It consists of different exercises such as: A) “Waterfall Jump”: The player stands on the edge of a waterfall and has to jump onto oncoming pieces (footprints) of wood in order not to fall down. While the frequency, size and order of the footprints vary the player has to jump with one or two legs in order to hit the footprints. B) “Stunt Run”: The player has to run on top of a running train and react quickly to upcoming obstacles. In order not to get hit, the player has to do sidesteps, jump over or duck down. C) “Derby Skate”: Comparable to aerobics or dancing, the player has to imitate and learn new sequences of movements. D) “Knee up splash”: Every trial, the player has to remember a new order of colors, which is depicted on the right side of the screen. The player has to pick colored melons in the order of the depicted colors (e.g., green, red, blue) and smash the melons at one's knee. As soon as he starts picking up the melons, the order disappears, meaning the participant has to rely on his memory. After each correct trial, one more melon has to be remembered and picked up. E) “Volcano Skate”:

The player has to skate up a volcano by performing skating movements. Once the player reaches the top, he has to skate downhill and react/ jump over upcoming barriers. F) “Slalom Grove”: This exercise is comparable to “Derby Skate”. Thus, the player has to imitate sequences of movements related to slalom skiing. In each activity, a higher score can be achieved through more movement and by performing the movements more precisely.

As can be seen from this example, the workouts mainly include a training of strength, coordination (and endurance), as well as demands on cognitive functions such as inhibition, switching, updating, attention and speed of action. In two previous studies, this exergame has been shown to be cognitively and physically challenging, and acute effects on the EFs have been reported^{38,39}. Moreover, it has been compared to purely physically challenging aerobic exergaming and was found to be more cognitively challenging than the latter³⁸.

Background and Manipulation check variables. Before the intervention as background variables, age and gender were gathered, height and weight were measured; to gather information about pubertal developmental, socioeconomic status and physical activity behavior, parents completed the pubertal developmental scale,⁴⁰ the family affluence scale⁴¹ and the physical activity, exercise, and sport questionnaire⁴². In addition, parents had to report their children’s medication use (medicament and dosage) and were asked to report any changes to the principle investigator during the study. In a supervised first exergaming training session, the heart rate was assessed using a Polar Team2 belt. The OMNI scale of perceived exertion⁴³ was used as a subjective measure of physical exertion. The scale ranges from 0-10, including corresponding verbal anchors from “not tired at all” to “very, very tired”. An adapted version of the self-assessment manikin was used as subjective measure of cognitive engagement⁴⁴. During the intervention, to get further insight about implementation fidelity, children had to fill out diaries including the duration of the training and the valence during training using the valence dimension of the self-assessment manikin (SAM)⁴⁵. After the intervention, enjoyment was assessed using three questions: 1) “How much did you like the

activity?” 2) “Did you feel comfortable doing the activity?” 3) “Did you enjoy doing the activity?”. The questions had to be answered on a 4-point Likert scale ranging from 1 = “not at all” to 4 = “very much”. As an enjoyment score, the mean of the three items was calculated.

Primary outcome. In counterbalanced order, the three core EFs (inhibition, switching and updating) were measured before and after the intervention with three computer-based tests using E-Prime Software (Psychology Software Tools, Pittsburgh, PA). These tasks have been proven to be reliable and valid measures of EFs for children and adolescents ^{25,39,46-48}.

Inhibition was assessed using a modified Simon Task ⁴⁹. In the Simon task ⁵⁰, stimuli were presented on a computer screen and children had to respond with either a mounted left or right external response button. Two different targets (a blue or a yellow starfish) appeared either on the right or on the left side of the screen. Children were instructed to press the left (yellow) or the right button (blue) as quickly as possible when the yellow or the blue starfish appeared, independent of the side where it appeared. In congruent trials, the blue (or yellow) starfish appeared on the same side as the corresponding key. In incongruent trials, the blue (or yellow) starfish appeared on the side opposite to where the key was. All trials were separated by a central fixation cross. Interstimulus intervals varied between 500 and 1500 ms, and stimuli were presented in random order. The dependent variable was the mean reaction time for correct responses. There were 60 trials per time point, with a short break including positive feedback midway through the trials.

Switching was assessed using a modified Flanker task ⁵¹⁻⁵³. In this task, five red or yellow fish are depicted on a screen. Children are instructed “to feed the fish” by pressing either a left or right mounted external response button. The button press should indicate in which direction the fish have their mouth. Trials were presented in randomized order. The task consisted of 40 trials. In 20 of these trials, the fish were red and in another 20 trials, the fish were yellow. For the red fish, the fish in the middle was the target fish; for the yellow fish, it was the four flanking fish. Children had to adapt their response depending on the color of the stimuli and either feed the fish in the middle (red

fish) or the flanking fish (yellow fish). A switch between both rules was required in 20 trials, when the color of the stimuli changed (switching trials). As the dependent variable, mean reaction times of switching trials were calculated. To ensure that the participants understood the task correctly, they completed five practice trials before each block. If their performance was below 60%, they had an additional practice loop including another five practice trials. The interstimulus intervals were varied randomly between 800 to 1400 ms.

Updating was assessed by a modified version of the color span backwards task^{54,55}. In this task, coins of different colors appear one after another on the screen. The participants had to remember the color of the coins and verbally repeat their appearance in the reversed order. After a short explanation and three training trials, the first six trials started. They consisted of two coins each and if the child answered three or more trials correctly, the span was increased by one coin for the next six trials. The span was increased until the child made more than three mistakes. In this case, the test was terminated after conducting the remaining trials of the current span. The sum of correct responses was counted as outcome score.

Secondary outcome. *ADHD symptoms* were assessed using the German version of the Conners-3 scales⁵⁶. The questionnaire, with well-established reliability ($r = .85$), validity (see manual) and internal consistency (Cronbach alpha $> .85$), consists of 110 items (rated on a 4-point Likert scale) and was filled out by the children's parents⁵⁷. For the present study *t*-scores on DSM-IV-TR Symptom Scales (hyperactivity, inattentiveness and combined) were used to measure severity of ADHD. For a measure of general psychopathology, the global index score was used (*t*-score). *T*-scores of 60-64 are considered as borderline; *t*-scores of 65-69 are considered clinically elevated.

Motor ability was assessed using six out of eight test items of the German Motor Test⁵⁸. This test is based on a three-level model representing the multidimensional construct of motor ability. Motor ability refers to "general traits or capacities of an individual, that underlie the performance of a variety of movement skills"⁵⁹. Corresponding to the three-level model, the German Motor Test

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measures five basic motor abilities including endurance, speed, strength, coordination and flexibility^{58,60}. Except for flexibility (which is seen as more anatomically determined), these five motor abilities can be differentiated into more energetically- or information-oriented. This differentiation is made depending on their involvement of cognitive processes, consequently placing endurance on the energetically-oriented, strength in-between and coordination on the information-oriented side of the continuum⁶⁰. Since the intervention mainly trained the information-oriented side of the continuum, strength and coordination (and flexibility) were assessed (coordination: balancing backwards, jumping sideways; strength: sit-ups, push-ups, long-jump; flexibility: stand and reach). An acceptable validity (see manual) and reliability ($r = .82$) has been demonstrated for the German Motor Test⁵⁸. For the present study, raw scores were transformed to standardized z -scores. Z -scores of under 91.67 are considered far below average and under 97.5 below average; 98-102.5 are considered as average; z -scores of 103-108.33 are considered as above average. The total score (calculated by the mean z -scores of the six test items) was considered as dependent variable.

Statistical analyses. Statistical tests were performed using SPSS 25.0 (SPSS Inc., Chicago, IL, USA). As *outlier analysis*, trials with a reaction time under 150 ms were excluded as anticipatory (Flanker task: 0.2%; Simon task: 0.2%). In a next step, trials with reaction times deviating by more than 3 SD from the child's mean (Flanker task: 1.2%; Simon task: 1.7%) as well as incorrect trials were excluded. The pattern of results did not change with or without outlier analysis.

Background variables (age, gender, pubertal developmental status, socioeconomic status, physical activity behavior), as well as pre-test values in EFs, ADHD symptoms, general psychopathology and motor ability performance were compared using independent t -tests. ANCOVAs using the pre-test values as covariates were used to compare the EFs, symptoms and motor ability performance (dependent variables) between the two groups (independent variable). Cohen's d was reported as an estimation of effect size. The significance level was set at $p < .05$ for all analyses.

Results

Preliminary analyses. Background variables (see Table 1) and dependent variables (pre-test values) did not differ between groups ($ps > .05$). According to diaries, participants trained on average for at least 80 minutes per week, having a high valence (see Figure 1). The mean heart rate measured during the supervised first training session was $M = 145.57$ bpm ($SD = 10.84$). Comparable to a previous study³⁹, children reported to be both physically (OMNI scale: $M = 6.23$, $SD = 2.05$) and cognitively challenged ($M = 5.95$, $SD = 2.33$), having a high overall enjoyment ($M = 3.62$, $SD = 0.64$).

Primary outcome. Regarding EF performance (see Figure 2 and Table 2), for inhibition (Simon task), the exergaming group showed faster overall reaction times compared to the control group ($F(2, 48) = 4.08$, $p = .049$, $d = 0.58$). For switching (Flanker task), the exergaming group showed a faster task performance in switching trials compared to the control group ($F(2, 48) = 5.09$, $p = .029$, $d = 0.65$). No significant differences were detected in updating ($F(2, 48) = 0.50$, $p = .482$, $d = 0.20$) nor in accuracy scores of inhibition and switching ($ps > .05$).

Secondary outcome. Regarding ADHD symptoms and general psychopathology (see Table S2, available online), significant effects were detected on the total global index score ($F(2, 48) = 5.34$, $p = .022$, $d = 0.68$). Whereas no significant effects were detected on the DSM-IV-TR symptom scales ($ps > .05$). Regarding motor ability performance (see Figure 3), after the interventional period the exergaming group showed a significantly better total performance than the control group ($F(2, 48) = 7.69$, $p = .008$, $d = .80$). When looking at the single test items of the German Motor Test (see Table S2, available online), a significant effect could be obtained in jumping sideways ($F(2, 48) = 4.49$, $p = .039$, $d = .61$) as well as push-ups ($F(2, 48) = 4.73$, $p =$

.035, $d = .63$). In all other test items, no significant differences between the two groups were detected ($ps > .05$).

Discussion

This study gives insights into the potential benefits of 8-weeks of cognitively and physically demanding exergaming on EFs, ADHD symptoms, general psychopathology and motor abilities of children with ADHD. Results show that exergaming can benefit EFs, general psychopathology and motor abilities.

Concerning the primary outcome, it seems that cognitively and physically challenging exergaming can improve EFs with regard to reaction times in inhibition and switching. This is in line with the limited empirical evidence on the positive effects of traditional physical exercise for cognitive performance in children with ADHD^{14,20}, and with the larger evidence on healthy children^{12,22}. Along with being physically active, the use of exergaming (in a virtual environment) might have contributed to the benefits obtained. Exergaming seems to benefit motivation, which might increase the potential to foster cognitive performance in children with ADHD. It has, for example, been shown that exergaming increases motivation and engagement in physical activity, eliciting motivational gains, as well as flow, immersion and enjoyment^{61,62}. However, since the intervention was compared to a wait-list control group, motivation has not been examined in the current study. Therefore, further research is warranted to investigate whether physically and cognitively challenging exergaming is equally beneficial to either cognitive or physical exercise training regarding commitment, motivation as well as outcome.

A combination of physically and cognitively challenging exergaming improved reaction times in inhibition and switching, but no changes were observed in updating and accuracy scores. These results extend findings of a recent meta-analytic review of physical exercise in ADHD²⁰, in which the authors point out that the most robust effects of physical exercise seem to be on inhibition, and results remain unclear with regard to switching and updating. Results of the current study, however, indicate that in addition to inhibition ($d = 0.58$), switching might also benefit ($d = 0.65$). Albeit, further research

is needed to examine the circumstances that lead to benefits for switching, and whether specific exercise characteristics (such as cognitive engagement) might be an important factor.

Corresponding to a previous meta-analysis on acute exercise and working memory ⁶³, in this study only positive effects on reaction times could be obtained. However, since a ceiling effect was evident for response accuracy, one could speculate that the additional attentional resources could only be allocated to response speed. Another potential explanation may be found within the inhibition task used. It might be that a task which is more closely related to the control of impulses and in particular the stopping of ongoing responses could more sensitively detect changes in accuracy elicited by physical activity. It remains unclear whether exergaming can or cannot benefit response accuracy in children with ADHD. Considering that response accuracy as well as updating accuracy are highly important for academic achievement ⁶⁴, exergames specifically targeting these domains should be developed and investigated (using for example the stop-signal task) in future.

The positive effects in inhibition and switching are in line with a study finding short term improvements in the same two components ³⁹. It is striking that in previous acute studies only positive effects were found on inhibition and shifting in children with ADHD (e.g., ⁶⁵⁻⁶⁸). Although the effects of acute and chronic physical activity do not have to correspond ⁶⁹, similar results could be interpreted in support for the neurobiological hypothesis ¹⁵. Within the neurobiological hypothesis it is assumed that physical activity might induce catecholamine neurotransmission, and since neurotransmission of for example noradrenaline and dopamine is frequently disrupted in children with ADHD ⁷⁰, this might increase cognitive performance in the short term. In the long-term, physical activity might lead to neurogenesis/angiogenesis and neuroplasticity in brain areas underlying EFs and ADHD symptomatology ^{18,19,70}, which consequently may improve performance. However, given this explanation it still remains unclear why updating was not improved.

Considering the cognitive stimulation hypothesis ^{21,23,24}, this circumstance might be explained by the qualitative physical activity characteristics. It may be that in the applied exergame the inhibition and switching components are needed to a greater extent than updating for successful task

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performance. Therefore, motor and cognitive functions underlying brain areas were stimulated during acute exergaming. Because this stimulation was only 15 minutes long, it did not deplete resources and might have increased the level of arousal, consequently leading to short term improvement in executive function performance³⁹. In the long term, the stimulation of brain regions responsible for higher order cognition might have trained these two EF components leading to improved performance. Since this interpretation is somewhat speculative, research is needed to further investigate the relationship between acute and chronic physical activity. Therefore, to investigate the contributions of acute effects and training gains to long-term improvement in future exergaming studies, the performance of each single training session could be recorded, and a short EF assessment applied afterwards.

Regarding secondary outcomes, a positive effect was found for exergaming on the total score of the German Motor Test. Additional analyses on the level of the single test items, however, showed that this significant result was mainly driven by the two items measuring coordination under time pressure and upper extremity strength. These results can be explained considering the specific exercises entailed in the applied exergame, and the similarity between them and the outcome assessment. When having a closer look on these exercises, coordination under time pressure for example was specifically trained in an exercise called “waterfall jump”. In this exercise, the participant has to jump from one foot to another or from left to right, onto fast oncoming pieces of wood. Since in the assessment of the German Motor Test participants have to jump sideways within 15 seconds as many times as possible, this is an example of a high similarity between training and outcome. In contrast, because there was no specific training of flexibility, an improvement in the stand and reach task was less probable. Taken together, the results show that specific motor abilities (strength, coordination) were trained to a greater extent, and therefore seem to underlie the positive effect on the total score. Thus, when considering that many children with ADHD also suffer from developmental coordination disorder⁵, a positive effect in coordination might be a promising effect.

Although not all motor abilities improved due to the training, the benefits in motor ability performance (total score) might still be of importance for children with ADHD because they a) frequently have difficulties taking part in traditional sports programs without dropping out ³¹; b) spend on average about twice as much time playing sedentary video games ³²; and c) often suffer from deficits in EFs, as well as gross and fine motor skills ⁴. Since physical inactivity is a major health factor in children and adults due to the many harmful effects on both physical and mental health ¹⁵, in future, exergaming could become an important tool to reach individuals that could not be reached by alternative methods. Furthermore, it could place the focus on health promotion through exercise, encouraging children and adolescents who are overtaxed by traditional programs. Since this is somewhat speculative, studies comparing exergaming to traditional exercise in children with ADHD are needed.

In the current study, the general psychopathology of the exergame group significantly ameliorated from “clinically elevated” to “borderline”. This seems in line with the limited studies on the effects of physical exercise on core ADHD symptoms ⁷¹. In contrast to most studies so far, the current study considered core ADHD symptoms and general psychopathology as outcomes, (surprisingly) finding only significant effects on general psychopathology. An explanation for the findings of the current study may be found by considering the results of a recent study. Skogli et al. (2017) detected that an association between improvements in ADHD symptoms over time were only linked to improvements in working memory ⁷². Since in the current study no effect on working memory performance was detected, one could assume that the intervention did not affect ADHD symptoms, or the statistical power was too low to detect these effects. In addition, Skogli et al. (2017) indicated that the linkage between cool EFs and hyperactive/ impulsive symptoms might be less close when symptomatology is less pronounced. Therefore, it might be that the current study also, the link between EFs and symptoms was less strong. Since hot EFs may be more closely related to ADHD symptoms such as impulsivity, future studies should focus on the effect of physical activity characteristics on both hot and cool EFs ⁷³, and their association with ADHD symptoms. Furthermore, considering the frequent finding of intra-individual variability in reaction times in children with ADHD ⁷⁴, the above proposed

investigation could further be enriched when looking at the impact of physical activity on intra-individual reaction time variability (reaction time distributions), and whether it is related to ADHD symptoms⁷³.

This study has some limitations, which are important to note. First, for ecological validity reasons, and in contrast to most cognitive training studies, we refrained from giving incentives to the children; nor did we do weekly calls and give feedback about the training frequency. This circumstance might have led to a relatively high dropout rate in the exergaming condition. Unfortunately, seven children did not want to participate in the post test and discontinued the study. This dropout might have introduced bias into the analyses, and although exergame interventions have shown to be feasible and increase physical activity and motivation³⁰, the high drop-out rate indicates that even with exergaming it is difficult to maintain regular training for children with ADHD. Second, the exergaming group was compared to a waiting-list control group. Therefore, the probability for an improvement due to the additional attention (“Hawthorne effect”) and not due to the intervention itself is increased compared to an active control group. This might be apparent particularly when considering that the children’s parents rated the ADHD symptoms and general psychopathology. Therefore, caution is warranted in the interpretation of these results. Third, the chosen exergame was not specifically customized for children with ADHD. Even though it included both cognitive as well as physical demands, the specificity of the training might have been suboptimal regarding qualitative exercise characteristics. We believe that a customized training, which is specifically designed to challenge the EFs, could lead to greater benefits for cognition. Fourth, even though the sample size was large enough to detect small to medium effects of the intervention, the statistical power was too small to additionally investigate relationships between variables. Larger studies including more children with ADHD and a follow-up assessment are needed to fully examine the potential of exergaming and, for example, determine whether gains in EFs are related to gains in psychopathology and/or motor ability. Fifth, since the intervention used was a commercial product, we were unable to obtain performance data and had to rely on children’s diaries. The check of implementation could therefore be improved by future studies, using device-derived data to objectively measure treatment fidelity. A final limitation was that neither

comorbidities such as developmental coordination disorder nor day to day changes in medication were specifically assessed. Although motor ability performance was examined using the German Motor Task, this is not a test battery specifically developed to assess motor function impairments. Therefore, it might be that this test is not as sensitive as commonly used assessments such as the Movement Assessment Battery for Children to determine whether motor skills are substantially below the expected of peers. For medication, we asked the parents to inform us about every change in medication. Future studies could assess day by day changes in medication, to better control for medication adherence and continuity.

Conclusions and perspectives

The findings of the present study indicate that exergaming has the potential to foster cognitive performance in children with ADHD and might in future serve as an adjunct to medical and psychotherapeutic treatments. Exergaming fostered benefits for EFs (reaction times in inhibition and switching), general psychopathology and motor abilities. Since exergaming is highly scalable, it could be a safe environment for clinical patients suffering from cognitive deficits to benefit EFs and replace sedentary screen time. However, there was a high drop-out rate in the exergaming condition and no benefits on updating and ADHD symptoms could be detected. Therefore, customized exergames specifically targeting ADHD symptoms in the intervention, as well as including improvements in child appropriateness, cognitive, and physical challenge are warranted.

Acknowledgements

This clinical trial was supported by the foundations “Stiftung Suzanne und Hans Biäsch zur Förderung der Angewandten Psychologie” and “Hans & Annelies Swierstra Stiftung”. We would like to thank the participating children and parents. You did a great job! We also gratefully acknowledge the help of Elpos and especially Martina Nydegger. Thank you for carrying out the assessments to Erika Marti, Sara Schüpbach, Nicola Biesold, Remo Burri and Jacqueline Hangl. A special thanks to Denise Wenk

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and Gina Galli for your dedicated work in this project. The authors declare that they have no conflict of interest.

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Table 1. Participant characteristics.

	Exergaming (<i>n</i> = 28)	Control (<i>n</i> = 23)
	<i>M (SD)</i>	<i>M (SD)</i>
Age	10.46 (1.30)	10.39 (1.44)
Gender (% male)	86.4 %	81.8 %
Height (cm)	144.70 (9.21)	143.99 (10.07)
Weight (kg)	35.50 (6.89)	39.32 (13.25)
Pubertal developmental status (3-12)	3.74 (0.97)	3.46 (0.72)
Socioeconomic status (0-8)	6.41 (1.35)	6.23 (1.51)
Physical activity behavior (minutes/week)	141.41 (134.70)	163.71 (150.32)
ADHD Diagnosis	100 %	100 %
Medication	71.4 %	73.9 %
<i>ADHD symptoms (DSM-IV)</i>		
Hyperactivity	63.08 (4.73)	62.96 (6.20)
Inattentiveness	64.19 (4.70)	62.65 (7.11)
Combined	64.64 (4.45)	63.29 (6.18)
<i>General psychopathology</i>		
Global index score	66.14 (4.45)	65.10 (6.78)
<i>Motor ability performance</i>		
Balancing backwards	98.79 (12.44)	99.87 (9.41)
Jumping sideways	103.68 (10.84)	103.74 (9.20)
Sit-ups	88.85 (9.22)	92.43 (8.73)
Push-ups	98.82 (9.81)	102.00 (10.74)
Long-jump	97.46 (9.51)	99.96 (9.44)
Stand and reach	104.89 (13.41)	101.22 (9.84)
Total	98.43 (6.84)	99.96 (5.69)

M = mean; *SD* = standard deviation

Table 2. Descriptive and inferential statistics of ANCOVAs comparing reaction times of executive function performance between groups.

	Exergaming (n = 28)		Control (n = 23)		<i>p (d)</i>
	Pre-test	Post-test	Pre-test	Post-test	
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	
<i>Simon Task (mean reaction times in milliseconds)</i>					
Inhibition	590 (99)	537 (88)	626 (107)	607 (117)	.049
<i>Flanker Task (mean reaction times in milliseconds)</i>					
Switching	1055 (291)	874 (156)	1077 (292)	1002 (290)	.029
<i>Color span backwards (sum of correct responses)</i>					
Updating	14.00 (2.73)	15.54 (3.80)	13.57 (3.61)	14.44 (3.92)	.482

M = mean; *SD* = standard deviation; *p* = *p*-value; *d* = Cohens *d*

Figures

Figure 1

Average weekly training duration (in minutes) and valence rating (error bars represent the standard error of the mean).

Figure 2

Model-estimated marginal means and standard errors of the mean of core executive function performance.

ms = milliseconds. * $p < .05$.

Figure 3

Model-estimated marginal means and standard errors of the mean of motor ability performance.

* $p < .05$.

Supporting information

Figure S1.docx

Table S2.docx

Table S3.docx





