Effects of Desk-Bike Cycling on Phonological Working Memory Performance in Adolescents With Attention Deficit Hyperactivity Disorder

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We investigated the effects of active workstations on cognitive control functions in individuals diagnosed with Attention Deficit Hyperactivity Disorder (ADHD). In a fully counterbalanced randomized control design, we examined the effects of cycling on a desk bike on phonological working memory (WM) in 18 adolescents with ADHD. Adolescents performed a phonological WM test across two separate sessions during which they either cycled or not. It was hypothesized that participants would perform better on the WM task while cycling as compared to seated-rest. Results showed that total WM performance was not affected by desk-bike cycling. Exploratory analyses suggested that cycling during more difficult trials (i.e., high WM demands) is beneficial for WM performance. More research is needed to shed light on how task difficulty moderates the potential compensatory effect of desk-bike cycling on WM performance in adolescent ADHD participants.

Keywords: desk bikes, active workstations, phonological working memory, ADHD, adolescents

INTRODUCTION

Effects of Desk-Bike Cycling on Phonological Working Memory (WM) Performance in Adolescents With ADHD.

Despite evidence that points to positive associations between physical activity, cognitive function (Hillman et al., 2008), academic performance (Castelli et al., 2007; Donnelly et al., 2016), and overall health (Butte et al., 2007) in school-aged youth, children's opportunities to engage in physical activities during the school day have significantly decreased during the last two decades (Institute of Medicine, 2013). This trend has co-occurred with the increasing prevalence of sedentary behaviors in western society due to advances in technology and environmental changes (Ng and Popkin, 2012) and contributes to chronic health problems across the life span, such as obesity and cardiovascular diseases (Hillman et al., 2008). As a response to these negative developments, organizations have begun to promote physical activity in the classroom (National Association for Sport and Physical Education et al., 2008). In addition, there has been a gradual increase in studies investigating the impact of active teaching lessons or active workstations on health and cognition (see also Kibbe et al., 2011; Donnelly et al., 2016; for a review see Mavilidi et al., 2018; Ruiter et al., 2019).

Recently, it has been suggested that physical activity interventions are especially beneficial for those children characterized by lower cognitive control and self-regulatory behavior[1] (Drollette et al., 2014). That is, overall findings revealed that a single, acute bout of moderate-intensity aerobic exercise facilitates cognitive performance, with more extensive effects observed for the lower-performing group than the higher-performing group on a flanker task. Similarly, Mahar et al. (2006) reported that increasing physical activity opportunities in the classroom to improve on-task behavior were especially beneficial for children who demonstrated poor on-task behavior at baseline. One specific class of individuals with cognitive control impairments is children diagnosed with attention deficit hyperactivity disorder (ADHD). Attention deficit hyperactivity disorder is a psychological outcome that manifests itself during childhood and is characterized by developmentally inappropriate levels of inattention, impulsivity, and hyperactivity (Rapport et al., 2009). Contemporary leading theories have explained the mechanism underlying ADHD-related deficits as an imbalance in the catecholaminergic systems in the brain, leading to dysfunction of attentional circuits (Rapport et al., 2009). Specifically, it has been hypothesized that attentional impairments may be due to depleted levels of dopamine in the prefrontal cortex. The efficacy of psychostimulants in the treatment of ADHD supports this notion (Yu-Kai et al., 2012).

Pontifex et al. (2013) investigated the effect of a single bout of moderate-intensity aerobic exercise on children with and without ADHD using objective measures of attention and brain neurophysiology. Although both groups improved performance on the flanker task following exercise, acute exercise appeared to have an additional benefit for children with ADHD. The ADHD group exhibited an increase in a neuroelectric component (i.e., error-related negativity, ERN) that has been linked to the upregulation of processes involved in action monitoring. Importantly, these exercise-induced facilitations in action monitoring processes resulted in increased task performance following errors in the ADHD group only.

Apart from the reported benefits of physical activities, such as aerobic exercise, recent studies also suggest that self-initiated spontaneous motor activity seems to serve as a positive function for children with ADHD. Rapport et al. (2009) noticed that the relationship between increased rates of activity and ADHD is pervasive, as the disorder is associated with excessive gross motor activity and fidgeting from early childhood (Corkum et al., 1998; Rapport et al., 2009), in both children and adults (Teicher et al., 2012). Moreover, also during the performance of cognitively demanding tasks (i.e., WM, stop-signal, and choice tasks), increased levels of activities among children and adults diagnosed with ADHD have been reported (Rapport et al., 2009; Alderson et al., 2012; Hudec et al., 2014). Rapport et al. (2009) hypothesized that increased movement may serve as a compensatory function to augment chronic cortical under-arousal associated with ADHD (Dickstein et al., 2006). In other words, hyperactivity is a functional and secondary symptom

reflective of unconscious efforts to increase arousal to meet cognitive WM demands. This model therefore predicts a positive relation between gross motor activity and cognitive performance for persons with ADHD. Indeed, this functional WM model was substantiated with recent findings showing that higher rates of spontaneous motor activity predicted significantly better phonological WM performance (Sarver et al., 2015) and better cognitive control performance (Hartanto et al., 2016) for children with ADHD. However, findings also showed that increasing set size demands within the context of a phonological WM task was not significantly related to an activity level as one should expect when adhering to the functional model (Rapport et al., 2009; Sarver et al., 2015).

With these recent findings, the widespread assumption that excess gross motor activity interferes with children's ability to actively engage in learning-related activities that challenge executive functions, such as WM, and the subsequent recommendations or measures to target this hyperactivity in the classroom, should be reconsidered. Instead of decreasing the activity levels of children and adolescents diagnosed with ADHD, research should investigate how opportunities for physical activities, particularly, ones that are neither disruptive nor stigmatizing, can be used in academic settings to help children perform cognitively demanding tasks. One promising strategy for increasing physical activity in the classroom is through the use of active workstations, such as desk bikes (Torbeyns et al., 2014; Ruiter et al., 2017).

Given the role of physical activity on cognitive function and academic performance, the aim of the present study was to investigate whether an exercise that is concurrent and of light intensity (i.e., self-paced cycling on a desk bike) could increase cognitive control of adolescents diagnosed with ADHD. Most research in the acute exercise literature has found positive effects on cognitive control processes *after* at least 20 min of moderate exercise (e.g., Hillman et al., 2003) in adults. To our knowledge, very few studies have investigated the effectiveness of a seated concurrent light intensity physical activity for preadolescents or adolescents diagnosed with ADHD (Sarver et al., 2015; Ruiter et al., 2019). Therefore, in the present study, the effects of structured motor activity on a desk bike on phonological WM performance in adolescents diagnosed with ADHD were examined. Desk-bike cycling was used in the study given its feasibility (i.e., allows students to stay seated and is relatively quiet) and affordability to be used in a classroom setting. Based on findings in previous work in which higher rates of spontaneous motor activity predicted significantly better phonological WM performance for children with ADHD (Sarver et al., 2015), it was hypothesized that adolescents with ADHD would benefit from cycling on the desk bike (i.e., concurrent light-intensity activity) and consequently show higher WM performance during cycling than during seated-rest. Since cycling on a desk bike is considered a light intensity activity in this study, no hypothesis was formulated for effects after cycling. We also explored whether WM performance during cycling would be differentially affected by WM load. In addition, we explored the effects of desk-bike cycling on subjective measures of mental effort, enjoyment, and difficulty.

[1]The term "cognitive control" refers to processes that allow information processing and behavior to vary adaptively depending on current goals and include interrelated processes of inhibition, working memory (WM), and cognitive flexibility (Diamond, 2013).

MATERIALS AND METHODS

Participants

Participants were 18 students of a special education school in the Netherlands (age, 15.62 ± 2.20; gender, 17 men), who were recruited through a newsletter and a special participation request letter sent *via* the school to the parents of 49 eligible adolescents. All participants had received the formal diagnosis of ADHD by their psychologist or psychiatrist using the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-V) criteria. Given generalizability concerns, adolescents with comorbidities were included. Out of the 18 participants, 10 had a comorbid diagnosis with an Autism Spectrum Disorder, and four with other comorbid diagnoses (i.e., persistent depressive disorder, attachment disorder, adjustment disorder, developmental coordination disorder, and Tourette syndrome). Twelve children were prescribed psychostimulants at the time of assessment. Parents of participants who were taking psychostimulants were asked to withhold these for a minimum of 24 h prior to participating in all assessment sessions. Furthermore, participants were asked to refrain from drinking coffee or high-sodium drinks. This study was approved by the university's Institutional Review Board.

Apparatus

One height-adjustable desk, one desk bike (Worktrainer), and one laptop (Lenovo B590, 15.6 in.) was used in the study. The cycling resilience was kept equal across participants.

Design and Procedure

The present study employed a fully counter-balanced, within-subjects repeated measures design. Each participant took part in two assessment sessions with repeating phonological WM tasks under different conditions. Each session was separated by approximately 8 days (range 5–16). Participants were tested in the same order and in the same room on both occasions. Randomization and counterbalancing of participants occurred before the first session to minimize learning and order effects (i.e., seated-rest–cycling vs. cycling–seated-rest). The students were individually taken out of class, brought to a quiet room, and were seated on a desk bike approximately 0.6 m from a laptop placed on a height-adjustable desk. The resistance rate was kept equal across students and sessions. Participants were given instructions about the task and had to practice several trials. In the cycling condition, they were asked to ride the desk bike for 2 min in order to familiarize themselves with the apparatus and to find a stable, endurable pace of their preference. In the non-cycling condition, participants were asked to sit still for 2 min on the desk bike. After this, the task started and participants completed it while cycling or engaging in seated-rest. Performance was monitored at all times by two trained research assistants who were seated in the same room, but outside participants' view and who wrote down the participants' oral answers. During both sessions, participants were recorded with a camera to register their responses. A session lasted for 30 min.

Measures

Phonological Working Memory Task

The phonological WM task is similar to the Letter-Number Sequencing subtest on the Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV; Wechsler, 2003) and assesses phonological WM based on Baddeley's (2007) model by requiring both central executive processing/manipulation and phonological storage-rehearsal. This cognitive task has often been used in ADHD research (e.g., Rapport et al., 2008; Sarver et al., 2015). Participants were presented with a series of jumbled numbers and a capital letter on a laptop. Each number and letter (4 cm height, font Arial) appeared on the screen for 800 ms, followed by a 200 ms interstimulus interval. The letter was never presented in the first or last position of the sequence to minimize potential primacy and recency effects and was counterbalanced across trials to appear an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Participants were instructed to verbally recall the numbers in order from smallest to largest and ending with the letter (e.g., the sequence 3 H 5 8 is correctly recalled as 3 5 8 H). See **Figure 1** for a graphical representation of the phonological WM task.

Each participant was administered the phonological task at four different cognitive loads (i.e., phonological set sizes consisting of 3, 4, 5, and 6 stimuli) across the two testing sessions. The four WM set size conditions, each contained 24 unique trials of the same stimulus set size, were counterbalanced across the two testing sessions to control for order effects and potential proactive interference effects across set size conditions (Conway et al., 2005). Before the start of the task, five practice trials with four stimuli were given to the participants. The research assistant would let the student practice until the 80% correct criteria were achieved.

Two trained research assistants, shielded from the participant's view, recorded the oral responses. Uncertainties and discrepancies regarding the oral responses were overcome *via* audio-video review. Performance data were calculated using partial-credit unit scoring (proportion of stimuli correct per trial) due to its preferred psychometric properties relative to all-or-nothing scoring (Conway et al., 2005) and control for differences in the number of stimuli available for recall across the set sizes.
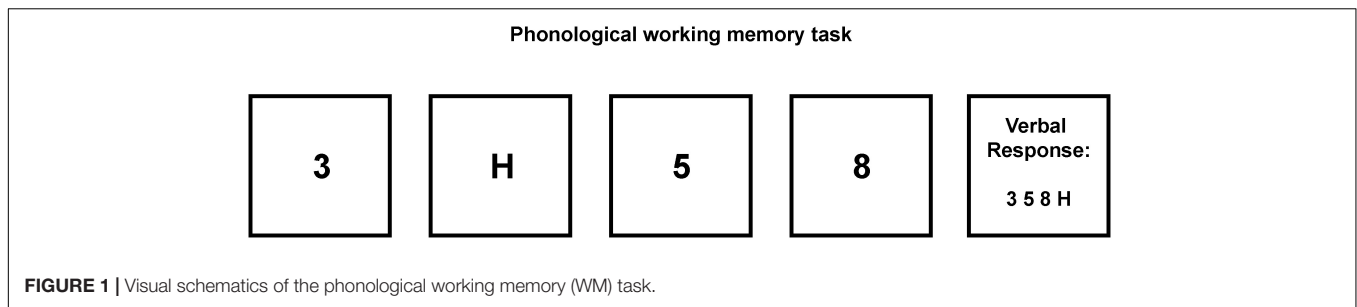
Task Evaluation

After task completion, participants were asked to rate their subjective task experience on aspects of difficulty ("How difficult was the task?"), enjoyment ("How much did you enjoy the task?"), and effort ("How much effort did you invest during the task?") on a nine-point Likert scale varying from 1 (very, very low) to 9 (very, very high).

RESULTS

Preliminary Analyses

To check for potential confounding effects of counterbalancing the order of the cycling condition, we ran an additional 2 × 4 mixed ANOVA on proportion correct score where session order (counterbalancing order: seated-rest first, cycling first) was

Phonological working memory task

FIGURE 1 | Visual schematics of the phonological working memory (WM) task.

included in addition to the factors of our main analysis. Results showed no significant interaction effects on proportion correct of counterbalancing order with cycling condition, $F_{(1,16)} = 0.075$, $p = 0.788$, $\eta^2_{partial} = 0.005$, indicating that counterbalancing order did not impact the effect of our experimental manipulation.

Phonological Working Memory

Descriptive statistics are shown in **Table 1**. The hypothesis that participants would perform significantly better on the WM task while cycling as compared to seated-rest was tested with a one-way repeated measures ANOVA. The dependent variable was task performance (i.e., total test scores), whereas the independent variable was test condition (i.e., cycling vs. seated-rest). When compared task performance while cycling ($M = 0.775$, $SD = 0.147$) with task performance while sitting ($M = 0.763$, $SD = 0.139$), results indicated that there was no statistically significant difference and thus no statistically significant effect of cycling on task performance compared to sitting; $t(17) = -0.614$, $p = 0.548$, $d = 0.08$. This result demonstrates that students performed on a very similar level on the cognitive task despite the change in test conditions.

We also looked at the effect of condition on the WM task at four different cognitive loads (i.e., phonological set sizes consisting of 3, 4, 5, and 6 stimuli). Mauchly's test indicated that

the assumption of sphericity had been violated for the main effect of WM scores, $\chi^2 (5) = 13.94$, $p = 0.016$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.66$). There was a significant main effect of WM set size on task performance, $F_{(1.98,33.64)} = 58.06$, $p < 0.001$, $\eta^2_{partial} = 0.77$, with higher set sizes corresponding with decreased performance (see **Table 1**). There was no significant main effect of condition on task performance, $F_{(1,17)} = 0.68$, $p = 0.421$, $\eta^2_{partial} = 0.04$. Mauchly's test also indicated that the assumption of sphericity had been violated for the interaction effect of WM Scores x Condition, $\chi^2 (5) = 18.51$, $p = 0.002$. Again, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.62$). There was a significant interaction effect between condition and WM set size scores, $F_{(1.86,31.71)} = 3.50$, $p = 0.045$, $\eta^2_{partial} = 0.17$. This suggests that conditions had different effects on participants' scores depending on which set size was given.

To explore this interaction as depicted in **Figure 2**, two paired sample t-tests were performed comparing the low (i.e., set sizes 3 and 4) and high (i.e., set sizes 5 and 6) WM set sizes across different conditions. The first paired sample t-test comparing cycling and seated-rest during WM set sizes 3 and 4 revealed no difference between the scores for seated-rest ($M = 1.78$, $SD = 0.19$) and cycling ($M = 1.74$, $SD = 0.26$), $t(17) = 1.11$, $p = 0.284$, $d = 0.02$. Another t-test compared the scores at WM set sizes 5 and 6 revealed a marginally significant difference between cycling ($M = 1.35$, $SD = 0.36$) and seated-rest ($M = 1.24$, $SD = 0.38$), $t(17) = 2.07$, $p = 0.054$, $d = 0.08$. Taken together, these results point in the direction of a specific trend: at low levels of load, WM performance is unaffected by cycling, but when set sizes increase, cycling seems to result in higher WM scores as compared to seated-rest.
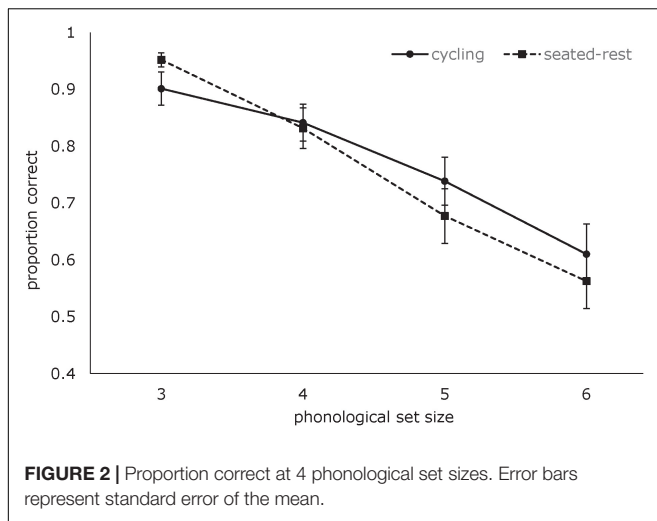
Task Evaluation

Due to the ordinal nature of the task evaluation scores, a Wilcoxon Signed Ranks Test was conducted to compare the effects of both conditions on the dependent variables "task difficulty," "enjoyment," and "mental effort." No significant differences were found between conditions for task difficulty ($Z = -0.960$, $p = 0.337$), enjoyment ($Z = -1.745$, $p = 0.081$), or mental effort ($Z = -0.086$, $p = 0.932$). Consequently, cycling during the WM task did not make a statistically significant difference for participants' rating of task difficulty, enjoyment, and effort as compared to seated-rest. Hence, the task evaluation scores do not offer an explanation for the results.

TABLE 1 | Means (SDs) of working memory (WM) performance and task evaluation measures across conditions.

Measure	Condition			
	Cycling		Seated-rest	
1. WM performance				
a. Set size 3	0.90	(0.12)	0.95	(0.05)
b. Set size 4	0.84	(0.14)	0.83	(0.51)
c. Set size 5	0.73	(0.18)	0.68	(0.20)
d. Set size 6	0.61	(0.23)	0.56	(0.20)
e. Total WM performance	0.77	(0.15)	0.76	(0.14)
2. Task evaluation				
a. Task difficulty	5.44	(1.51)	5.83	(1.58)
b. Mental effort	5.56	(1.79)	5.44	(2.25)
c. Enjoyment	4.56	(1.85)	5.42	(2.14)

WM performance scores are in proportion to stimuli correct. Task evaluation scores were measured on a 9-point Likert scale.

FIGURE 2 | Proportion correct at 4 phonological set sizes. Error bars represent standard error of the mean.

DISCUSSION

This study is the first one to examine whether physical activity in the form of stationary cycling can be used in the classroom to help adolescents diagnosed with ADHD perform cognitively demanding tasks. Based on literature pointing toward a positive association between motor activity and cognitive control for adolescents with ADHD (Drollette et al., 2014; Sarver et al., 2015; Hartanto et al., 2016), we hypothesized that exercise in form of cycling during a phonological WM task would result in increased WM performance. Yet, no statistically significance of cycling was found on total WM performance. The present study therefore fails to substantiate the assumption that facilitating physical activity helps adolescents with ADHD improve their WM performance. This result is in line with several previous studies failing to find a beneficial effect of active workstations on cognitive functioning (Bantoft et al., 2016; Torbeyns et al., 2017). It is important to note, however, that these earlier results have arrived with a different population, namely, adults or typically developing children and not children or adolescents diagnosed with ADHD.

As an additional exploratory analysis, we also looked at the effect of condition on WM task performance at low and high levels of the cognitive load instead of total WM performance. Data revealed that at low levels of load (i.e., set sizes 3 and 4), seated-rest and cycling resulted in comparable WM scores, whereas cycling resulted in better WM performance when set sizes increase (i.e., set sizes 5 and 6).

This result is in line with the study of Hartanto et al. (2016) who found that higher rates of spontaneous motor activity predicted significantly better performance on inhibitory control. In their study, participants' movements were measured by affixing an actometer to their ankles that measured their level of activity while completing the flanker test. The accuracy of the participants with ADHD was significantly improved when they were moving. In other words, correct answers were associated with more motion than incorrect answers. This result suggests

that accuracy in ADHD may be enhanced by more intense activities or that when a child with ADHD is using more cognitive resources they are more likely to be engaging in physical activity. One possible mechanism for a relationship between movement and cognitive performance is that children with ADHD use movement to self-regulate alertness. An optimal level of arousal is required for peak cognitive performance (Yerkes and Dodson, 1908). The results of the present investigation and the study of Hartanto et al. (2016) support Rapport et al.'s (2009) model that hyperactivity may serve to compensate for underarousal and acts to improve cognitive performance.

Another explanation for this result can be found in the fact that cycling on a desk bike is a very specific form of structured, continuous movement with the lower body. Possibly, this type of movement will prevent adolescents with ADHD from making more uncontrolled movements with the upper body (e.g., arm movements) that are unrelated to the task at hand and that negatively affect task performance, since they take away the attention necessary for well-performing a task under high WM load conditions (Engle, 2002). More specifically, cycling movements have the potential to channel the surplus of motor activity common to adolescents with ADHD, while keeping a focus on the challenging cognitive task at hand. As a result, performance under high WM load conditions will be increased, while no such performance gains are obtained in tasks under low WM conditions. This explanation resonates well with findings that continuous body movements, as opposed to discrete movements, increase performance on WM tasks under conditions of high cognitive load (Maes et al., 2015). More research is needed to shed light on how task difficulty moderates the potential compensatory effect of cycling on task performance, especially, in children with ADHD. These findings have important implications for the educational field or clinical practice. Desk bikes can be implemented in the classroom to help manage students' hyperactivity symptoms and boost their performance in the classroom on cognitively demanding tasks, without interrupting, or distracting peers or teachers in the classroom.

Limitations and Future Studies

In the present study, cycling was self-paced and mandatory. While the small sample size with the presence of comorbid diagnosis may limit the study's ability to draw robust conclusions, the study is a first step toward examining the effect of concurrent light-intensity exercise on cognitive control. Future studies should replicate the study using a cadence sensor and multiple actigraph devices to gain a deeper insight into activity patterns of the upper and lower body associated with adolescents with ADHD. In addition, the inclusion of a cadence sensor in future studies can also shed light on the complex interplay between motor activity and different WM demands both during conditions of seated-rest and cycling. It would also be interesting to investigate whether mandatory or self-regulated cycling would differentially affect WM performance, since in the latter situation one can manage one's own cognitive load.

Another limitation of the present study is that we exclusively looked at one single phonological WM task and we did not employ pre- and post-test experimental designs. Due to the diffuse nature of the WM construct, multiple tasks tapping the same construct but differing in other respects (e.g., design, modality) would provide a more robust outcome measure than using a single test alone. For instance, one can use the Digit span task, another common neuropsychological test in the WISC-IV battery to assess auditory WM. This task involves repeating a sequence of numbers in the same order right after they have been read aloud. This test differs from the phonological WM test, in which a screen was used to present the numbers and letters. Another essential step would be to investigating the relationship between visuospatial WM and physical activity. This is especially important, since evidence points out that concurrent motor movements, such as finger tapping (e.g., Della Sala et al., 1999), have been shown to produce interference with this aspect of WM. In addition, by using pre- and post-test experimental designs, future studies could also verify if desk-bike cycling increases cognitive performance at an individual level. By doing so, we will be able to investigate different parameters, such as intensity, type of task, individual characteristics, and self-initiation, to understand the mechanism underlying the effect of spontaneous physical activity.

This study was conducted in a controlled classroom setting with limited distractions over a short time period. We recommend follow-up studies with a larger sample size to investigate the long-term effects of desk bikes in a more naturalistic environment. It could not only be investigated whether movement on a desk bike translates to improved WM, which is critical for several academic tasks (Alloway and Alloway, 2010), but more importantly, whether it leads to improved academic attainment among adolescents with ADHD.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Review Committee at the Department of Psychology, Education and Child Studies of Erasmus School of Social and Behavioral Sciences. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

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