Improving Executive Function of Children with Autism Spectrum Disorder through Cycling Skill Acquisition

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ABSTRACT

TSE, A. C. Y., D. I. ANDERSON, V. H. L. LIU, and S. S. L. TSUI. Improving Executive Function of Children with Autism Spectrum Disorder through Cycling Skill Acquisition. *Med. Sci. Sports Exerc.*, Vol. 53, No. 7, pp. 1417–1424, 2021. **Purpose:** Executive dysfunction has been widely reported in children with autism spectrum disorder (ASD). Although studies have clearly documented the cognitive benefits of physical exercise on cognition in children, similar studies in children with ASD are scarce. The purpose of this study was to compare the effect of cognitively engaging exercise and noncognitively engaging exercise on executive function in children with ASD. **Methods:** Sixty-two children diagnosed with ASD (50 males and 12 females, $M_{\text{age}} = 9.89 \pm 1.53$ yr, $M_{\text{height}} = 1.43 \pm 0.15$ m, and $M_{\text{weight}} = 44.69 \pm 11.96$ kg) were randomly assigned into three groups: learning to ride a bicycle ($n = 22$), stationary cycling ($n = 20$), and control ($n = 20$). Four executive function components (planning, working memory, flexibility, and inhibition) were assessed. **Results:** Results revealed significant improvements in all executive function components in the learning to ride a bicycle group ($P\text{s} < 0.05$) but not in the other two groups after controlling for age and IQ. **Conclusion:** Our findings highlight the value of cognitive engagement in exercise programs designed to improve cognition in children with ASD.

Key Words: COGNITIVE FUNCTION, COGNITIVE ENGAGEMENT, MOTOR LEARNING, PHYSICAL EXERCISE, CHILDREN

Autism spectrum disorder (ASD) is an increasingly prevalent neurodevelopmental disorder evident from early childhood. In Hong Kong, the latest prevalence rate is 1.5%, and the rate is predicted to increase (1). Children with ASD are characterized by persistent deficits in social communication and social interaction, along with restricted and repetitive behavior, interests or activities (2). In addition to these core symptoms, executive dysfunction is also widely reported and has been conceptualized as a neuropsychological feature in the ASD population (for a review, see Lai et al. [3]). Executive function is a multifaceted cognitive construct that consists of several interacting but potentially dissociable components: planning, flexibility, working memory, and inhibition (4). Planning is the process that identifies and organizes a sequence of steps to achieve a goal (5). Flexibility is the ability to switch attention between tasks (5). Working memory refers to the capacity to hold and manipulate information in mind across a short period (6). Inhibition refers to the ability to suppress or avoid a prepotent response to make a less automatic but task-relevant response (7).

Deficits in the components of executive function are believed to contribute to many autistic behaviors, such as restricted and repetitive behavior patterns (4) and communication (8), as well as social impairments (9). For instance, inflexibility in switching between rules governing behaviors or changing conversational topics could result in social impairments (9). Deficits in working memory limit the capacity to hold task-relevant information in mind and contribute to maladaptive emotional behaviors in difficult problem solving situations (10).

The aforementioned high-prevalence and negative consequences of executive dysfunction in children with ASD highlight the importance of developing effective intervention strategies to improve executive function in this population. Currently, computer-based cognitive training and strategy-based training (i.e., specific EF training) are the two main intervention strategies for ameliorating executive function problems in children with ASD (11–13). Despite some reports of improvements in executive function in children with ASD, these types of training are intensive (e.g., 20 $\text{h} \cdot \text{wk}^{-1}$) and complicated, and they require specific equipment (e.g., Cogmed working memory training battery [14]) or copyrighted protocols (e.g., Unstuck and On Target curriculum 12). Moreover, research studies on these interventions have generally had small sample sizes (11–13) and lacked a transfer task (13) (i.e., did not assess whether improvements transferred to other skills such as communication and social skills). Therefore, the evidence for training efficacy related to improving executive function remains inconclusive.

By contrast, a significant body of research has investigated the effects of physical exercise on executive function in

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typically developing children. Several meta-analytical reviews have provided compelling evidence that physical exercise positively affects children's cognition and executive function (15–17). For example, the most recent meta-analysis of 36 studies (*n* = 3805) by Álvarez-Bueno et al. (16) examined the effects of physical exercise interventions on children's cognition and metacognition. Overall results indicated that physical exercise programs benefit multiple components of executive function, including working memory, selective attention-inhibition, and cognitive flexibility.

Although physical exercise has been shown to benefit executive function, most of the studies were conducted with typically developing children (15–17). Studies of exercise and executive function in children with ASD are very limited. Nonetheless, most of the studies support the cognitive benefits of physical exercise in these children (for a review, see Tan et al. [18]). For example, Ringenbach et al. (19) showed that assisted cycling therapy improved inhibition and cognitive planning in adolescents with ASD. Pan et al. (20) used a 12-wk table tennis intervention merged with executive function training for 22 children with ASD to examine the effect of such an intervention on motor skill proficiency and executive function. Results revealed significant improvements in motor skill proficiency and executive function after the intervention (20). More recently, Bremer et al. (21) demonstrated that a circuit-based workout led to improved inhibition control in 12 male children with ASD, with the increase in their cerebral oxygenation occurring immediately after the exercise intervention.

Given the benefits of physical exercise on executive function, its low cost, ease of administration, and health benefits, physical exercise may be an excellent alternative way to ameliorate the executive function problems in children with ASD. However, with a limited number of studies directly measuring the effect of physical exercise interventions on executive function in children with ASD (20), limited sample sizes (21), and incomprehensive measures of executive function (18), the effect of physical exercise interventions on executive function remains uncertain.

Therefore, in this study, we compared changes in the four components of executive functioning (planning, working memory, flexibility, and inhibition) following two types of physical exercise interventions. We randomly assigned participants to one of three groups: 1) learning to ride a bicycle (cognitively engaging exercise), 2) stationary cycling (noncognitively engaging exercise), and 3) no exercise (control). Learning to ride a bicycle was chosen because it is a developmentally appropriate, yet challenging, physical exercise that enables children to play with their friends and family and extend their social networks (22,23). More importantly, it is a natural and common physical exercise. It has been proven feasible to teach children with ASD to ride a bicycle, and cycling has been shown to increase children's physical exercise levels and improve their social behavior (23,24). Importantly, learning to ride a bicycle is physically and cognitively demanding, and it aligns with the cognitive stimulation hypothesis proposed by Best (25) and Pesce (26). The hypothesis maintains that cognitively stimulating exercise is more likely than noncognitively stimulating exercise to induce improvements in cognitive function.

We hypothesized that learning to ride a bicycle would require higher cognitive effort and therefore benefit executive function more than stationary cycling. We were uncertain whether stationary cycling would lead to significant improvements in executive functioning. Several studies with typically developing children have shown that acute bouts of exercise and chronic exercise have positive effects on executive function (e.g., Tomporowski et al. [27]). However, the current intervention was too short to induce the changes in brain structure and function thought to underlie changes in executive function in children exposed to chronic exercise interventions. In addition, the posttest assessments were too long after the end of the intervention for the children to reap the benefits of the increased blood flow to the brain, arousal and attention thought to underlie changes in executive function in children exposed to acute bouts of exercise.

METHODOLOGY

Study Design

The proposed study was a three-armed randomized controlled trial design with equal allocation ratio to the two intervention groups and one control group (1:1:1).

Data Collection

Each participant underwent two assessments in their respective schools, where we assessed different components of their executive function. The cognitive assessments were performed on two consecutive days, and each assessment lasted for 30 min at the most to prevent cognitive fatigue in the participants. The sequence of all cognitive assessments was counterbalanced to prevent order effects. The two assessments were conducted 2 d before the intervention (T1: preintervention) and 1 d after the 2-wk-long cycling interventions or regular treatment (T2: postintervention). Figure 1 is the CONSORT flow diagram.

Sample Size Calculation

The sample size was based on the most relevant two previous studies examining the effect of physical exercise on cognition in children with ASD (20,28), which showed that physical exercise had strong enhancement effects, corresponding to a Cohen's *d* of 1.69 (28) and 1.02 (20) on executive function. If the effects of our intervention were similar to those in these two studies, a sample of 16 participants per group was required to achieve a power of 80% and a level of significance of 5%. Assuming 20% attrition, 20 participants were required in each group.

Participants

Initially, 77 participants were recruited from three local special schools for children with mild intellectual disability and from parent's recommendations. The inclusion criteria were as follows: 1) age 8–12 yr; 2) mild to moderate ASD (i.e., level

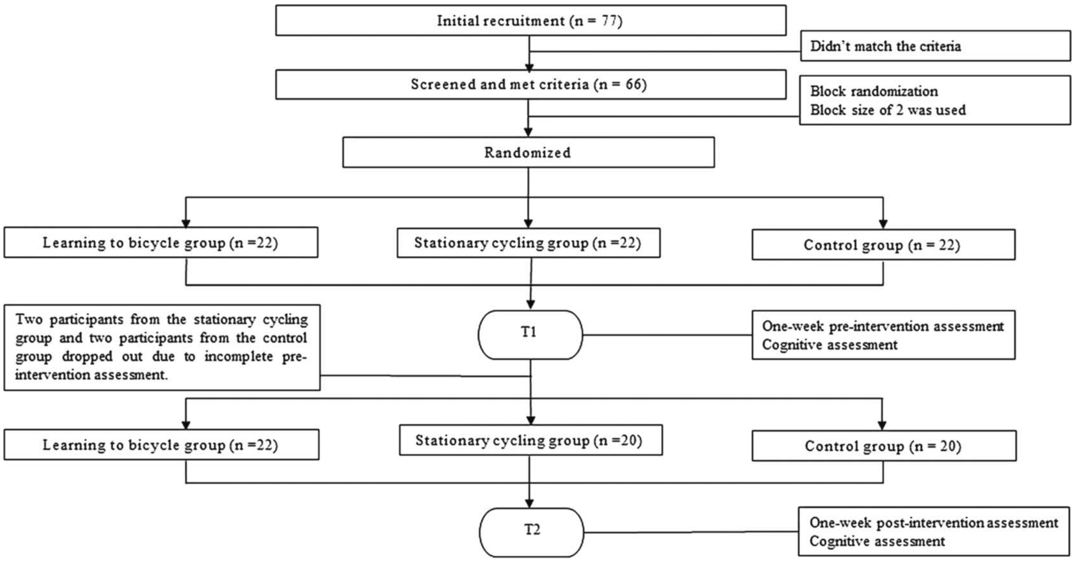

FIGURE 1—CONSORT diagram.

1–2 support classification [29]) diagnosis from physicians or psychologists based on the *Diagnostic and Statistical Manual of Mental Disorders, 5th edition* [2] and the *Autism Diagnostic Observation Schedule, 2nd Edition* [30]; 3) nonverbal IQ over 40 using a brief version of the *Wechsler Intelligence Scale for Children* (Chinese revised) (for more information, see Gong and Cai [31]); 4) able to follow instructions with the assistance of research staff; 5) able to perform the requested physical intervention and executive function measures with the assistance of the research staff; 6) no additional regular participation in physical exercise other than school physical education classes for at least 2 months before the study; and 7) novice at riding a two-wheel bicycle (i.e., cannot ride the bicycle alone for more than 10 consecutive seconds).

The exclusion criteria were as follows: 1) other medical conditions that limited physical exercise capacities (e.g., asthma, seizure, and cardiac disease); 2) a complex neurologic disorder (e.g., epilepsy, phenylketonuria, fragile X syndrome, and tuberous sclerosis); 3) suffering from obesity (i.e., >95 percentile of age- and gender-specific BMI cutoff [32]), such that it would be difficult for research staff to catch them if they began to fall when riding; and 4) self-reported color blindness. In addition, we also collected parent ratings of autistic traits and autism behaviors using the Social Responsiveness Scale, Second Edition [33], information for each participant from the parents, including records in after-school group therapy (e.g., occupational therapy and speech therapy), and medication usage. After screening, a total of 66 participants joined the study, and they were randomly assigned to the two exercise intervention groups and the control group. However, two participants from the stationary cycling group and two participants from the control group dropped out in the middle of the study. Consequently, 62 participants (22 in the learning to ride a bicycle group, 20 in the stationary cycling group, and 20 in the control group) successfully completed the study. Written consent was obtained from participants' parents/guardians. The study was approved by the university's ethics committee. Demographic data for the two groups are shown in Table 1.

Randomization

After screening, all the eligible participants were randomly assigned to the two intervention groups or the control group. To ensure equal allocation ratios for the intervention groups and control groups, block randomization (34) was used. A block size of two was used in the proposed study. A trained research assistant completed the block randomization process.

Intervention

Learning to bicycle group. This intervention was a 2-wk bicycle training program consisting of 10 sessions (five sessions per week, 60 mins per session) in a hall/gymnasium of each participating school and the Education University of Hong Kong. Each intervention session was conducted by a professional cycling instructor assisted by student helpers. The staff-to-participant ratio was 1:1. Each intervention session was conducted in an identical format, comprising three activities: warm-up (10 min), bicycle training (40 min), and cooldown (10 min). In the bicycle

TABLE 1. Demographic of participants (*n* = 62).

	Learning to Ride a Bicycle Group (*n* = 22)	Stationary Cycling Group (*n* = 20)	Control Group (*n* = 20)	*P*
Gender	19 boys and 3 girls	16 boys and 4 girls	15 boys and 5 girls	
Age (yr)	10.23 ± 1.66	9.55 ± 1.57	9.85 ± 1.31	0.36
Weight (kg)	45.47 ± 12.32	41.55 ± 12.12	46.97 ± 11.30	0.34
Height (m)	1.43 ± 0.15	1.39 ± 0.17	1.46 ± 0.13	0.39
BMI (kg·m^{-2})	21.78 ± 2.86	21.02 ± 2.33	21.97 ± 3.61	0.57
Nonverbal IQ	56.68 ± 6.54	57.95 ± 8.51	54.15 ± 6.32	0.24
Social Responsiveness Scale, Second Edition, raw scores	71.00 ± 8.66	70.25 ± 8.24	71.55 ± 7.91	0.88
Medication (*n*)				
Yes	4	2	3	
No	18	18	17	

training activity, participants were asked to ride on a training bicycle with training wheels to gain better control of the bike in a gradual way. Participants then progressed from the training bicycle to a two-wheel bicycle. To keep participants on the learning curve, they were asked to ride through an obstacle course that was progressively more difficult to negotiate. The obstacles were designed by a focus group, which consisted of four physical education teachers from participating schools and one experienced cycling coach with more than 5 yr of coaching experience. Because most of the participants were reluctant to wear the heart rate monitors, the exercise intensity level was measured by asking participants every 10 mins during exercise to indicate their RPE (target range, 3–5) with the OMNI scale (35). Participants were positively reinforced verbally with compliments for their efforts in the training program, and their daily improvements were visualized through graphs kept in the child's bedroom at home.

Stationary cycling group. Participants in this intervention group received a 2-wk stationary cycling program with a format identical to that in the learning to bicycle group (e.g., identical duration, identical manpower, identical warm-up, and cooldown). However, instead of learning how to ride a bike, participants were asked to ride on a stationary bicycle. Similarly, participants were asked every 10 mins during exercise to indicate their RPE (target range, 3–5). Participants were positively reinforced verbally with compliments for their efforts in the training program, and their daily improvements were visualized through graphs kept in the child's bedroom at home.

Control group. Participants in the control group received no exercise intervention (i.e., no cycling activity), and they were asked to maintain their normal routine without additional physical exercise during the study. After the study, they were taught how to ride a bicycle to recognize their contribution as controls.

Outcomes

Planning. Cognitive planning was assessed using a computerized Tower of London (TOL) task (InquisitPlayer version 6.2.2), which has previously been used with children with ASD (36). Participants were presented a sequence of three different colored balls (yellow, green, and red) on three pegs of different lengths. During each of the 12 trials, participants were instructed to move the balls to match the target peg arrangement in a specific amount of moves according to prespecified rules. The task was halted if there were three consecutive failed trial attempts. The level of task difficulty and the restriction on number of moves were progressively higher over time. As task difficulty and restrictions on moves increased, children were required to plan further ahead to ensure they matched the target peg arrangement without violating the task rules and restrictions. Scores for children's general planning ability were calculated by summing the correct tasks performed out of the 12 trials given, and the total scores ranged from 0 to 36 (37). The higher the score, the better the planning ability.

Working memory. Working memory was assessed by the Corsi block tapping task (CBTT [38]) and the forward digit span (FDS) and backward digit span (BDS) tests (39). These tests were used to measure the capacities of visual–spatial working memory and auditory working memory, and they had been used previously with children with ASD (40). In the CBTT, participants were first asked to observe the sequence of blocks being "tapped" and then were asked to repeat the sequence in order. The initial sequence length was three blocks, and after every two trials, the sequence length increased by one. The task ended after two incorrectly repeated sequences of the same length, and the longest correctly repeated sequence length was recorded. The longer the sequence length, the larger the number of items that could be stored in working memory and the higher the visual–spatial working memory capacity. For the digit span tests, digits were presented at a rate of one digit per second, and participants were required to repeat the sequence verbally. The initial sequence length was two digits, and the sequence length increased by one after every two trials. The test ended after two incorrectly repeated sequences of the same length, and the maximum digit span was established. Similar to the CBTT, the longer the spans that the participants could memorize, the higher their working memory capacity.

Flexibility. The Stroop Color and Word Test (SCWT [41]) was used because it has been used previously to measure cognitive flexibility in healthy and ASD populations (9,42,43). In the present study, we used the most common version of the SCWT by Stroop (1935), where the participants are required to read three different tables as fast as they can. The three different tables were classified into two conditions: congruent and incongruent conditions. In the congruent condition, participants were first required to read the names of the colors printed in black (W) (first table) and name different color patches (C) (second table) (42). After that, they were asked to read the third table, where words are printed in different colors (e.g., the word "yellow" is printed in red ink) (CW) (42). The cognitive flexibility score, which is represented by the interference score (IG), is calculated using the formula $IG = CW - (W \times C)(W - C)$. This formula was used because it has been the most frequently used in previous studies (for a review, see Scarpina and Tagini [42]). The lower the IG, the better the cognitive flexibility.

Inhibition. The participants' ability to inhibit unwanted responses to changing stimuli was measured by a computerized Go/No-go (GNG) task and was identical to the one used by Tse et al. (40). In the task, participants were asked to press a left or a right key as quickly as possible when the corresponding arrow appeared on the center of the computer screen (Go response), and not to press any key whenever the up arrow appeared on the screen (No-go response). Following 20 practice trials, participants completed 300 trials: 220 trials requiring a Go response (110 left and 110 right) and 80 trials (26.7%) requiring a No-go response (not pressing any key) (40,44). The stimuli were randomly presented, one at a time, for 500 ms followed by 1000 ms of blank interval using E-Prime 3.0 software (Psychology Software Tools Inc., Pittsburgh, PA). After blocks of 60 trials, children were offered a break of 2 min. No feedback was given upon response, and the response time was recorded but not analyzed because of the unreliability of the recording procedure (40). As in the study of Uzefovsky et al. (44), a Go response in a No-go trial was coded as a false alarm (FA). FA errors are considered an indicator of inhibition, the lower the better.

Each participant was asked to complete each task administered by either a trained research assistant or a trained student helper. All the tests were administered by the same research staff for consistency.

Blinding

The staff responsible for the cognitive assessments and data analyses were blinded to the group assignment.

Statistical Methods

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) for Windows (version 27.0; SPSS Inc., Chicago, IL). All the data were entered into SPSS by the research assistant. An independent-samples *t*-test was used to compare the OMNI scores between the two intervention groups. One-way (three groups: learning to bicycle vs stationary cycling vs control) repeated-measures ANCOVA was performed on each EF outcome to compare the changes between and within groups over different periods. Considering the potential confounding effects of developmental factors, age and IQ were controlled as covariates. Bonferroni *post hoc* analyses were performed when any significant difference was found in any of the outcome variables. Bonferroni correction was used to adjust the alpha levels (i.e., $P = 0.05 / 3 = 0.02$).

RESULTS

No significant differences were found in the OMNI scores for the learning to bicycle group ($M = 4.0$, SD = 1.07) and the stationary cycling group ($M = 4.60$, SD = 1.42), $t_{40} = -1.55$, $P > 0.05$, which implied that the mean exercise intensity levels were similar in the two groups.

All the neuropsychological measures were comparable between groups at T1 (see Table 2).

Planning. As shown in Table 2, there was a significant group–time interaction effect ($P < 0.001$). The learning to ride a bicycle group showed a significant increase in the TOL raw score ($P < 0.001$) from T1 to T2 with a medium effect size ($d = 0.45$). By contrast, the stationary cycling group and the control group did not show any significant change in the TOL raw score (all *P*s > 0.05) from T1 to T2 with small effect sizes ($d = 0.03$ and 0.1). This result suggested that only the bicycle learning intervention was effective for improving participants' cognitive planning.

Working memory. There were three assessments for working memory: FDS, BDS, and CBTT. No interaction effects were observed for FDS and BDS (*P*'s > 0.05). No groups showed any significant improvements in FDS during the study. However, analyses revealed that the learning to ride a bicycle group and the control group showed significant increase in BDS from T1 to T2 with small effect sizes ($d = 0.17$ and 0.24). Meanwhile, the repeated-measures ANCOVA indicated a significant interaction effect for the CBTT ($P = 0.004$). The bicycle learning group showed a significant increase in the CBTT score from T1 to T2 ($P = 0.01$) with small effect size ($d = 0.24$) whereas the other groups did not.

TABLE 2. Comparisons of neuropsychological measures between groups and within groups at different timeslots.

Neuropsychological Assessment	Learning to Ride a Bicycle Group (SD)	Stationary Cycling Group (SD)	Control Group (SD)	*P* (Group Effect)	*P* (Interaction Effect)
Planning (TOL raw score)					<0.001
T1	11.00 (10.39)	13.20 (9.82)	10.40 (10.29)	0.66	
T2	18.59 (10.06)	11.30 (11.26)	11.10 (9.67)	0.03	
P (time effect)	<0.001	0.22	0.66		
Cohen's *d* effect size (95% CI)	0.45 (0.20 to 0.69)	0.10 (−0.14 to 0.35)	0.03 (−0.21 to 0.29)		
Working memory (FDS)					0.07
T1	2.86 (2.36)	3.65 (2.433)	3.30 (1.98)	0.53	
T2	3.31 (2.21)	3.10 (2.29)	2.75 (1.80)	0.68	
P (time effect)	0.06	0.13	0.25		
Cohen's *d* effect size (95% CI)	0.13 (−0.12 to 0.37)	0.15 (−0.11 to 0.39)	0.14 (−0.10 to 0.39)		
Working memory (BDS)					0.86
T1	2.50 (1.90)	2.20 (1.32)	2.50 (1.28)	0.77	
T2	3.23 (2.11)	2.75 (1.68)	3.05 (1.36)	0.68	
P (time effect)	0.03	0.08	0.01		
Cohen's *d* effect size (95% CI)	0.24 (−0.01 to 0.49)	0.17 (−0.07 to 0.42)	0.17 (−0.06 to 0.41)		
Working memory (CBTT score)					0.004
T1	2.77 (1.60)	2.65 (1.09)	3.25 (1.29)	0.34	
T2	3.55 (1.82)	2.45 (1.53)	2.60 (1.67)	0.08	
P (time effect)	0.01	0.49	0.09		
Cohen's d effect size (95% CI)	0.27 (0.02 to 0.52)	0.07 (−0.18 to 0.31)	0.21 (0.03 to 0.46)		
Flexibility (SCWT IG)					0.002
T1	−4.17 (5.11)	−5.10 (5.09)	−3.21 (5.95)	0.54	
T2	−0.08 (9.03)	−6.45 (6.80)	−4.55 (7.16)	0.03	
P (time effect)	0.02	0.08	0.17		
Cohen's *d* effect size (95% CI)	0.33 (0.08 to 0.58)	0.10 (−0.15 to 0.35)	0.10 (−0.15 to 0.35)		
Inhibition (GNG FA error)					0.23
T1	16.00 (8.28)	17.15 (8.98)	20.60 (9.90)	0.13	
T2	12.50 (7.99)	18.25 (9.70)	22.20 (10.52)	0.01	
P (time effect)	0.02	0.62	0.62		
Cohen's *d* effect size (95% CI)	0.22 (−0.03 to 0.47)	0.06 (−0.18 to 0.31)	0.09 (−0.15 to 0.34)		

SCWT IG = Stroop Color Word Test Interference Score; GNG FA error = Go/No-go false alarm error.

Flexibility. Repeated-measures ANCOVA indicated that there was a significant interaction effect for SCWT IG. The bicycle learning group showed a significantly lower SCWT IG than the other two groups at T2 ($P = 0.03$). Within group, the bicycle learning group showed a significant drop in SCWT IG after the intervention ($P = 0.02$) with small effect size ($d = 0.33$), whereas the other two groups showed no differences in the score (Ps > 0.05) from T1 to T2.

Inhibition. No significant interaction effect was observed for the GNG FA error. Subsequent tests revealed that the FA error of the bicycle learning group was significantly smaller than that of the other two groups (P's < 0.02) at T2, and there was a significant reduction of FA error from T1 to T2 in the group ($P = 0.02$) with small effect size ($d = 0.22$). By contrast, no significant differences were observed in either the stationary cycling group or the control group from T1 to T2.

Comparisons of neuropsychological measures between groups and within groups at different periods are shown in Table 2.

DISCUSSION

The purpose of the present study was to compare how different exercise interventions (i.e., learning to ride a bicycle vs stationary cycling) affect cognition in children with ASD. It is the first study to incorporate a comprehensive measure of all executive function components. We hypothesized that the learning to ride a bicycle intervention would benefit executive function, although we were uncertain whether stationary cycling would have any effects on executive function. In line with our hypothesis, we found that the learning to ride a bicycle intervention was effective for improving planning, visual–spatial working memory, cognitive flexibility, and inhibition. By contrast, the stationary cycling intervention did not have any effects on any of the executive function components. The positive effects of the learning to ride a bicycle intervention are particularly impressive given the intervention had a duration of only 2 wk.

The current findings are consistent with those of a study by Schmidt et al. (42), in which a 6-wk-long football and basketball team games intervention (high cognitive engagement) was shown to improve shifting (i.e., cognitive flexibility) in typically developing children, whereas the cognitive performance of children in a 6-wk-long aerobic exercise intervention (low cognitive engagement) did not differ from those in a control group. These findings can potentially be explained by the cognitive stimulation hypothesis proposed by Best (25) and Pesce (26). According to the hypothesis, physical exercise should be cognitively demanding to challenge the higher-order cognitive processes (25,26) necessary to induce changes in cognitive functioning (45,46). We presumed that participants in the learning group would engage in extensive cognitive processing while they acquired the cycling skill, which in turn would lead to significant improvements in cognitive functioning. The early stages of skill acquisition are known to place heavy demands on cognitive processing (e.g., Magill and Anderson [47]). Although the stationary cycling intervention placed minimal demands on cognitive processing, we were uncertain whether it would lead to significant changes in executive function. It clearly did not yield any cognitive benefits. Indeed, the stationary cycling group's responsiveness to the intervention was consistent with findings of Dimond and Ling (41,44), which showed that an aerobic exercise intervention without any cognitive challenge was a less effective way to improve executive function than an exercise intervention with cognitive challenges (45,48). However, it is prudent to be cautious here. It is possible the stationary bicycling intervention would have been beneficial if it were longer in duration.

It is important to note that the learning to ride a bicycle intervention benefited all the executive function components. One of the strengths of the present study was that it incorporated a comprehensive assessment of executive function. The breadth of effect suggests that the intervention naturally placed demands on each executive function component. For example, participants need to plan a strategy for approaching the task and for making turns and following the cycling route once they were able to cycle independently (i.e., cognitive planning was trained). They needed to memorize and recall the movement sequences related to cycling (e.g., body position, pedaling action, and steering) and process information related to balance and visual–spatial information relating to their position in space relative to the physical layout, obstacles, and other people (i.e., working memory was challenged). Participants also needed to shift their attention constantly between their internal movements and the external environment (which changed regularly) and be prepared to switch their plans to respond to an unexpected event (e.g., someone ahead suddenly stopped or someone was cycling toward them) (i.e., cognitive flexibility was trained). They also needed to inhibit automatic responses to any distractions and keep their attention focused on the task and the coach's instructions, resisting any temptations that may have compromised safety (e.g., speeding up) (i.e., inhibition was challenged). All of the components of executive function were likely improved because they were constantly challenged by the learning to bicycle intervention.

Despite the strengths of the present study, several important issues require further investigation. First, we did not assess the level of cognitive engagement in the intervention groups. Without a measure of participants' cognitive engagement, or perceived cognitive effort, we cannot conclude unreservedly that cognitive engagement was the sole factor leading to improvements in the learning group. Future studies should consider incorporating such measurements. Second, the participants' stress levels and the level of social interaction between our staff and the participants were not measured in the present study. Literature shows that stress, mood, and social interaction are also closely related to executive functions (for reviews, see Moriguchi [49] and Shield et al. [50]). The learning to ride a bicycle intervention was thought to be more fun and more socially interactive than the stationary cycling intervention, and that difference may be responsible for the differences between the two groups. Further study is required to investigate this suggestion. Third, it is unclear which component of the learning to ride a bicycle intervention drove the positive effects on executive function. We suspect that two components: spatial updating during translation of the body through space and dynamic balancing on a narrow base of support, which can only be found in the learning to ride a bicycle group, are critical for facilitating the positive changes in executive function. In fact, studies have shown that dynamic balancing training and exercise that requires spatial updating (e.g., running) can improve cognitive function (e.g., memory, spatial cognition, and vocabulary learning) in healthy and older adults (51–53). However, no literature shows that balancing and/or translating through space influences executive functioning in children with ASD. Future research should explore this area. Finally, we should acknowledge that we have not attempted to explain the significant improvement in the BDS task in the control group because we currently do not have an explanation for it. Further research is needed to determine whether the improvement is replicable before it is wise to offer an explanation for it.

CONCLUSIONS

The present study shows that cognitively engaging exercise benefits executive function in children with ASD, whereas noncognitively engaging exercise does not. Practically, the current findings provide clinicians and teachers with a novel method to improve executive function in children with ASD. Teachers and caregivers can redesign physical education programs to bring added cognitive benefits to children with ASD.

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C. Y. A. T. designed the study and wrote the manuscript. V. H. L. L. and S. S. L. T. coordinated the data collection and implemented exercise interventions. D. I. A. designed the study and revised the manuscript. All authors read and approved the final manuscript.

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