

Effects of Flanker-based locomotor training on executive function and motor coordination in first-grade children

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Abstract

Background and Study Aim Executive function and motor coordination are components of cognitive and behavioral development during early childhood. Cognitive-motor interventions based on physically active tasks are increasingly used in school settings to support these developmental processes. Despite the application of various cognitively enriched movement approaches, their effectiveness in improving executive function and motor coordination through structured locomotor training remains a subject of practical interest. Therefore, the present study aimed to assess the effects of a Flanker-based locomotor training intervention on executive function and motor coordination in girls aged 6–7 years.

Material and Methods A cluster-randomized controlled trial was conducted among 192 girls aged 6–7 years from six private primary schools. Participants from three schools were assigned to the experimental group, which completed an 8-week Flanker-based locomotor training program. Executive function and behavioral self-regulation were assessed using the HTKS-R, and motor coordination was evaluated using KTK subtests. Group × Time intervention effects were analyzed using linear mixed-effects models adjusted for school-level clustering.

Results Significant Group × Time interaction effects were observed for executive function, Walking Backward, Hopping for Height, and Moving Sideways following the intervention (all $p < 0.001$). The experimental group demonstrated greater improvements in HTKS-R performance and selected motor-coordination outcomes compared with the control group. No statistically significant intervention effect was identified for Jumping Sideways ($p = 0.981$). Improvements were more pronounced in tasks requiring inhibitory control, response regulation, and adaptive movement adjustment.

Conclusions Flanker-based locomotor training was associated with improvements in executive function and selected aspects of motor coordination in girls aged 6–7 years. The findings suggest that the integration of cognitive-conflict and rule-switching tasks into structured locomotor activities may support cognitive-motor development during early childhood.

Keywords: cognitive-motor integration, inhibitory control, executive function, motor coordination, school-based intervention, HTKS-R

Introduction

Goal-directed behavior, school readiness, and adaptive functioning during early childhood are associated with executive functioning processes, including inhibitory control, working memory, and cognitive flexibility. These processes develop rapidly during the early years of education and are related to academic performance and behavioral regulation [1, 2]. Executive function is also associated with motor development, with consistent relationships

reported between motor competence and executive processes across childhood [3, 4]. In particular, motor skill learning and movement proficiency have been associated with improvements in executive functioning, especially during tasks requiring coordination, timing, and adaptive response control [5, 6]. This functional interaction highlights the relevance of approaches that simultaneously target cognitive and motor development in children.

Research indicates that physical activity contributes to cognitive development throughout childhood, particularly in the area of executive functioning. Physical activity has also been associated with improvements in attention, cognitive control, and academic performance [7, 8].

Evidence further suggests that the cognitive benefits of exercise may depend on how task demands are structured. In particular, interventions that include cognitively engaging components, such as decision-making, response inhibition, or task switching, may produce greater improvements in executive function than activities with lower cognitive demands [9]. These findings suggest that cognitive engagement and task complexity may influence the effectiveness of physical-activity interventions targeting executive function in children.

Researchers have increasingly focused on the qualitative characteristics of movement tasks rather than only on the general effects of physical activity on executive function. A common approach used to examine cognitive demands associated with movement activities involves structured tasks that require children to monitor their movements, inhibit automatic responses, and adapt motor actions according to changing task conditions. Related studies suggest that structured cognitive engagement during movement activities may support executive function and motor performance through the systematic integration of cognitive demands into motor tasks [10, 11]. Evidence also indicates considerable variation in how cognitive demands are implemented across interventions, with limited use of theoretically structured frameworks for integrating cognitive and motor activities. As a result, the mechanisms underlying cognitive-motor improvements remain difficult to interpret consistently.

Although research on cognitively enriched physical activity has increased, considerable variation remains in the conceptual structure and design of these interventions. Many studies have incorporated cognitive components without systematically targeting specific executive-function processes or clearly defining how cognitive and motor components interact during movement activities. As a result, the optimal integration of executive-function demands into motor tasks remains difficult to interpret consistently across intervention models. In addition, relatively few interventions have been based on empirically validated cognitive paradigms capable of providing controlled and replicable approaches for embedding cognitive demands into motor activities [12, 13]. The use of theoretically grounded approaches may improve the conceptualization of Cognitive Motor Integration (CMI) and support more structured examination of cognitive and motor development in children.

A potential approach to addressing these limitations involves the use of established cognitive paradigms capable of systematically manipulating executive-control processes. Among these paradigms, the Flanker Task is widely used to assess inhibitory control by requiring participants to respond to target stimuli while suppressing interference from adjacent distractors [14]. This paradigm provides a controlled

framework for examining response inhibition, conflict monitoring, and selective attention, which are components of executive function [15]. Recent evidence also supports the integration of cognitive-control processes into movement activities through the inclusion of cognitive-conflict conditions during motor-task performance [16, 17]. Adapting these approaches to locomotor training may provide a more systematic and theoretically grounded method for embedding cognitive demands into movement tasks.

Previous studies have identified the Head-Toes-Knees-Shoulders Revised (HTKS-R) as a commonly used behavioral measure for assessing self-regulation and executive-function processes in young children [18]. The HTKS-R evaluates inhibitory control, working memory, and cognitive flexibility through structured motor-response tasks and has demonstrated associations with academic and behavioral outcomes during early childhood development [19, 20]. In addition, recent studies conducted in Iraq have supported the applicability of the HTKS-R in educational settings involving children of preschool and early school age [21, 22].

The Körperkoordinationstest für Kinder (KTK) is widely used for the assessment of gross motor coordination in children [23, 24]. The KTK evaluates components of motor performance including balance, dynamic postural control, movement coordination, and agility, and has been applied in both educational and clinical settings involving children and adolescents [25]. Previous studies have also reported high reliability and applicability of the KTK for assessing changes in motor coordination across different pediatric populations [26].

Analysis of previous findings has shown that cognitively enriched movement activities may influence executive function and motor coordination during childhood development. Researchers emphasize the relevance of integrating cognitive-control processes and adaptive motor responses within structured locomotor activities. At the same time, variation in the organization and operationalization of cognitive demands continues to complicate the interpretation of cognitive-motor intervention effects. These aspects remain relevant for the development of more structured approaches to cognitive-motor integration in children.

In addition, researchers emphasize that the integration of executive-control processes into locomotor activities may provide a more structured approach to cognitive-motor intervention design. The use of cognitive paradigms involving inhibitory control, cognitive conflict, and adaptive response regulation may contribute to a more systematic organization of cognitively enriched movement activities. At the same time, the operationalization of cognitive demands within locomotor interventions remains methodologically diverse, which continues

to influence the interpretation of cognitive-motor intervention outcomes.

The aim of the present study was to examine the effects of Flanker-based locomotor training on executive function, behavioral self-regulation, and motor coordination in girls aged 6–7 years.

It was hypothesized that participants in the experimental group would demonstrate greater improvements in executive function and motor coordination than participants in the control group. It was further expected that intervention effects would be more pronounced in tasks requiring higher levels of cognitive regulation.

Materials and Methods

Participants

First-grade girls from all private primary schools in Samarra, Iraq, were recruited during the first semester of the 2025–2026 school year. At the time of the study, six private primary schools for girls in Samarra agreed to participate. A homogeneous sample of first-grade girls was selected to reduce developmental variability and support consistent intervention implementation across schools. The selection of participants from private schools also helped minimize variability in educational scheduling, classroom structure, and physical-education delivery. In addition, this sampling approach supported more consistent intervention implementation during an early developmental stage characterized by changes in executive and motor functions.

During the initial recruitment phase, 212 students were assessed for eligibility according to predefined inclusion and exclusion criteria. Following eligibility screening, 201 participants met the study criteria and were included in the intervention phase.

During the intervention period, nine participants were excluded from the final analyses because of school withdrawal or transfer, failure to meet the minimum attendance requirement ($\geq 80\%$ of intervention sessions), or exclusion according to HTKS-R administration criteria. After these exclusions, the final sample consisted of 192 girls aged 6–7 years.

Participants were allocated according to school-level group assignment. Three schools were assigned to the experimental condition ($n = 97$), and three schools were assigned to the control condition ($n = 95$). The number of participants per school ranged from 31 to 34 in the experimental schools and from 31 to 32 in the control schools.

- Eligibility criteria required participants to:
- be enrolled in the first grade of primary school;
- be aged between 6 and 7 years;
- have written parental consent for participation;
- have no medical or physical conditions limiting participation in regular physical-education activities.

Participants with medical or physical conditions preventing safe participation in physical education were excluded from the study. Participants who attended fewer than 80% of intervention sessions were also excluded. Additional exclusions were applied according to the HTKS-R administration manual.

Ethical Considerations

Before the commencement of the study, the research protocol was reviewed and approved by the relevant academic committee of the University of Samarra (Approval No. 18, approved on 2 July 2025). All study procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki for research involving human participants. Administrative approval was obtained from all participating schools prior to data collection. Written informed consent was obtained from the parents or legal guardians of all participants before inclusion in the study. Participants and their guardians were informed of the right to withdraw from the study at any stage without penalty. All collected data were treated as confidential and used exclusively for research purposes.

Study Design

This study used a cluster-randomized controlled design to examine the effects of Flanker-based locomotor training on executive function and motor coordination in first-grade girls. Consistent with the clustered structure of the educational intervention, schools served as the unit of randomization, whereas individual participants served as the unit of analysis. Appropriate statistical procedures were applied to account for the hierarchical structure of the data.

Six private primary schools for girls located in Samarra, Iraq, participated in the study. Three schools were assigned to the experimental condition, and three schools were assigned to the control condition. All eligible first-grade students within each participating school received the intervention corresponding to their school-level group assignment.

The intervention was implemented during regular physical-education classes to maintain consistency with routine school instruction. This approach supported the ecological validity and practical applicability of the intervention within a school-based setting.

A controlled pre-test/post-test design was used to assess outcome measures before and immediately after the 8-week intervention period. This design allowed evaluation of changes in executive function and motor coordination while accounting for the clustered structure of the data.

The study followed the CONSORT extension guidelines for cluster-randomized trials during the design, implementation, and reporting stages.

Randomization

A cluster-randomization procedure based on school-level allocation was used in the study. The six participating schools were randomly assigned to either the experimental or the control condition, with three schools allocated to each group.

The randomization process was completed prior to intervention implementation using a computer-generated random-allocation sequence. Because the participating schools were relatively similar in terms of grade organization and physical-education scheduling, no additional matching or stratification procedures were applied before randomization. Baseline equivalence between groups was subsequently examined across the primary outcome measures.

All eligible students within each participating school received the intervention corresponding to their school-level allocation. This approach ensured that the intervention was implemented at the cluster level in accordance with the study design.

Schools and teaching personnel were not involved in the allocation process. The randomization sequence was generated by a researcher who was not involved in outcome assessment prior to HTKS-R and KTK administration. Outcome assessors were blinded to group allocation and participant enrollment status during data collection.

Intervention Program

The intervention consisted of a locomotor-training program based on cognitively demanding Flanker-task conditions integrated into structured physical-education activities. The intervention was designed to engage executive-function processes during the performance of coordinated motor tasks.

The intervention was conducted over eight weeks and included three sessions per week, resulting in a total of 24 training sessions. Each 40-minute session included a 5-minute warm-up, 25 minutes of station-based training, brief transition periods between stations, and a 5-minute cool-down.

The training program was organized using a station-based format. Each class was divided into eight groups of four participants. Eight training stations were arranged throughout the sports hall along a rectangular movement area measuring approximately 12 m × 3 m. Participant groups rotated through the stations in a clockwise direction, allowing each group to complete all eight stations during each session. Each station was performed for approximately 3 minutes, followed by short transition intervals between stations.

The training tasks were developed according to Flanker-based cognitive-conflict conditions involving congruent and incongruent stimulus processing and response inhibition. Visual stimuli included directional arrows, colors, and geometric shapes presented on printed cards positioned either on the floor or in front of the participants. Locomotor

tasks were standardized using predefined stimulus-response mappings. Under congruent conditions, participants performed locomotor responses that matched the central target stimulus. Under incongruent conditions, participants were required to inhibit the dominant response and perform the opposite locomotor action while ignoring distracting flankers.

Representative locomotor activities included directional running between floor markers, lateral stepping tasks, multidirectional jumping sequences, and stop-go transitions in response to changing visual cues. Each station followed a structured sequence consisting of stimulus presentation, locomotor-response execution, and corrective feedback. Task difficulty was progressively increased through reduced response-preparation time, conflicting stimulus conditions, and alternating response rules.

To improve procedural reproducibility, stimulus-response rules were standardized across all intervention schools. For arrow-based tasks, the central arrow defined the target stimulus. During congruent trials, participants moved in the same direction as the central arrow. During incongruent trials, participants inhibited the dominant response and moved in the opposite direction while ignoring the flanking arrows. For color-based tasks, each color was assigned to a predefined locomotor action before the session, such as forward running, backward stepping, lateral stepping, or jumping. During rule-switching tasks, the stimulus-response rule was changed only after the teacher's verbal signal. All participants received identical task instructions, demonstrations, practice trials, and corrective feedback before completing each station.

The eight-week program progressively increased cognitive and motor-task demands across intervention phases through greater stimulus ambiguity, response conflict, and rule-switching complexity. During weeks one and two, participants practiced basic locomotor movements using congruent stimulus-response mapping. During weeks three and four, incongruent stimuli were introduced to create cognitive conflict between the presented stimulus and the required motor response. During weeks five and six, participants completed rule-switching tasks requiring changes in motor responses according to different stimulus-response rules. During weeks seven and eight, tasks combined multiple forms of cognitive conflict, including mixed stimulus conditions and scenarios requiring increased executive-function engagement.

All intervention sessions were conducted in the sports halls of the participating schools and delivered by physical-education teachers under the supervision of the research team. Prior to the intervention, teachers completed standardized preparatory training sessions that included practical demonstrations of task procedures, station organization, and

progression criteria to support consistent implementation across schools. A structured fidelity-monitoring procedure was applied throughout the intervention period and included regular supervision visits and standardized observation checklists. These checklists evaluated task delivery, session timing, progression implementation, and participant organization. Corrective feedback was provided when inconsistencies in implementation were identified. Attendance during the intervention period was high, with an overall participation rate of 91.7% across intervention sessions.

Teacher preparation included two standardized training sessions conducted before the intervention period. During these sessions, teachers practiced task delivery, stimulus presentation, station transitions, and progression procedures under researcher supervision. Fidelity observations were conducted weekly using structured checklists that evaluated adherence to task instructions, timing consistency, stimulus-presentation accuracy, participant organization, and progression implementation. Fidelity scores below the predefined implementation threshold resulted in corrective supervision and additional retraining.

Control Condition. Participants in the control group continued their regular school-based physical-education program during the study period. No participants in the control condition performed structured Flanker-based cognitive-motor tasks or cognitive-conflict activities. Physical-education classes in the control group were delivered with the same frequency and duration as those in the experimental group (three sessions per week, 40 minutes per session). Both groups therefore received comparable amounts of physical education, whereas only the experimental group participated in the Flanker-based locomotor-training program.

Outcome Measures. Anthropometric characteristics, executive function (primary outcome) assessed using the HTKS-R, and motor coordination (secondary outcomes) assessed using the Körperkoordinationstest für Kinder (KTK) were the outcome measures of the study. To minimize measurement bias, all assessments were conducted by three trained assessors who were blinded to group allocation. Prior training in testing procedures was completed to support consistent administration of outcome measures across all participating schools.

Anthropometric Measurements. Participants' height and body mass were measured before the administration of the motor and cognitive assessments. Height was measured to the nearest 0.1 cm using a portable stadiometer, with participants standing barefoot. Body mass was measured to the nearest 0.1 kg using a calibrated digital scale while participants wore light sports clothing. These measurements were recorded to describe participant characteristics and assess comparability between

the study groups.

Executive Function. Executive function was assessed using the Head-Toes-Knees-Shoulders Revised (HTKS-R). The HTKS-R is a behavioral assessment of self-regulation based on structured rule-following tasks involving motor responses. The assessment includes tasks targeting inhibitory control, working memory, and cognitive flexibility. All assessments were conducted in school-based settings. The HTKS-R consists of progressively more complex tasks requiring participants to perform motor responses opposite to verbal instructions (e.g., touching toes instead of touching the head). Cognitive demands increase through the introduction of more complex rule combinations involving inhibitory control, working memory, and cognitive flexibility. Scoring followed the standardized HTKS-R administration procedure. Two points were awarded for a correct response, one point for a self-corrected response, and zero points for an incorrect response or non-response. Total scores ranged from 0 to 118, with higher scores indicating greater levels of behavioral self-regulation and executive function. Administration time was approximately 5–7 minutes per participant and did not require specialized equipment.

Motor Coordination

Motor coordination was assessed using the Körperkoordinationstest für Kinder (KTK), which consisted of four subtests.

- Walking Backward (WB),
- Hopping for Height (HH),
- Jumping Sideways (JS), and
- Moving Sideways (MS).

Walking Backward assessed dynamic balance by requiring participants to walk backward along balance beams of decreasing width. Hopping for Height assessed lower-limb coordination through repeated single-leg hopping over progressively increasing obstacle heights.

Jumping Sideways assessed movement speed and coordination by requiring participants to perform repeated two-footed jumps over a small obstacle within a fixed time interval.

Moving Sideways assessed lateral movement coordination through repeated sideways transfers using two platforms within a fixed time interval.

Scoring and administration procedures followed the standardized KTK manual. Walking Backward scores were based on the number of successful steps completed across the balance beams. Hopping for Height scores were based on the number of successful hops completed over progressively increasing obstacle heights. Jumping Sideways scores reflected the total number of successful jumps completed during a 15-second interval. Moving Sideways scores reflected the total number of successful platform transfers completed during a 20-second interval.

Raw scores from each KTK subtest were used for statistical analysis.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corporation, Armonk, NY, USA) and R software (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was set at $p < 0.05$.

Descriptive statistics (means and standard deviations) were calculated for all variables before and after the intervention. The Shapiro–Wilk test was used to assess normality assumptions. Based on the distributional characteristics of the data and the sample size, parametric analyses were considered appropriate. Model diagnostics indicated no substantial violations of linearity or homoscedasticity assumptions.

The primary outcome measure was the HTKS-R total score assessing executive function. Secondary outcome measures consisted of motor-coordination subtest scores, including Walking Backward, Hopping for Height, Jumping Sideways, and Moving Sideways.

Baseline equivalence between the experimental and control groups was assessed using independent-samples t-tests for all outcome variables.

Linear mixed-effects models were used to examine intervention effects between the experimental and control groups. Group (experimental vs. control), time (pre-test vs. post-test), and the Group \times Time interaction were included as fixed effects, whereas school was included as a random effect to account for clustering within schools. This modelling approach allowed adjustment for the hierarchical structure of the data.

In addition, baseline-adjusted analyses of covariance (ANCOVA) were performed with post-test scores specified as dependent variables, group specified as a fixed factor, and pre-test scores included as covariates. ANCOVA analyses were conducted as complementary procedures to improve statistical precision and adjust for baseline differences between groups.

Linear mixed-effects models (LMM) and ANCOVA were both used to evaluate intervention effects while accounting for baseline performance and the clustered study design. Intraclass correlation coefficients (ICCs) were calculated to estimate the proportion of variance attributable to school-level clustering and to support the use of multilevel modelling procedures. Because only six clusters were included, cluster-robust standard errors with small-sample correction were applied.

Effect sizes for model effects were reported using partial eta squared (η^2p), whereas standardized mean differences were expressed using Cohen's d values based on adjusted means. Partial eta squared values were interpreted as small (0.01), medium (0.06), and large (0.14).

A Bonferroni correction was applied to adjust for Type I error associated with multiple testing of secondary outcomes. For motor-coordination

outcomes involving the four KTK subtests, the adjusted significance threshold was set at $p < 0.0125$ ($0.05/4$).

A post hoc statistical power analysis was conducted using G*Power software (Version 3.1.9.7) based on the observed effect sizes and sample size.

Complete-case analysis was used and included only participants who completed both pre-test and post-test assessments and met the predefined attendance and assessment criteria. Missing data were limited, and intervention attendance reached 91.7% across intervention sessions. Of the 201 eligible participants, nine were excluded from the final analyses because of school withdrawal or transfer, insufficient intervention attendance, or exclusion according to HTKS-R administration criteria. No systematic differences were identified between included and excluded participants.

Missing data were limited and distributed similarly between the experimental and control groups. The proportion of excluded participants represented less than 5% of the initially eligible sample. Baseline comparisons between included and excluded participants did not indicate differences in the primary outcome measures. Complete-case analysis was therefore applied to participants who met the predefined attendance and assessment criteria.

Results

Descriptive statistics (mean \pm SD) were calculated for all study variables at pre-test and post-test. The Shapiro–Wilk test was used to assess normality assumptions, and all variables met the criteria for parametric statistical analyses.

No statistically significant differences were observed between the experimental group (EG) and the control group (CG) for any outcome variable at baseline (all p -values > 0.05). Therefore, the groups were considered comparable across the assessed outcome measures before the intervention.

Changes from pre-intervention to post-test were observed across the study variables. The experimental group demonstrated improvements in executive function and behavioral self-regulation as measured by the HTKS-R, as well as improvements in motor coordination. In contrast, the control group demonstrated minimal or no changes across these measures. HTKS-R scores increased in the experimental group following the intervention, whereas scores in the control group remained relatively stable over the same period.

The experimental group also demonstrated improvements in Walking Backward, Hopping for Height, and Moving Sideways performance following the intervention. In contrast, little or no change was observed in the control group for these measures. Jumping Sideways performance did not demonstrate significant changes in either group

between pre-test and post-test assessments.

Table 1 presents descriptive statistics for all outcome variables at pre-test and post-test in both the experimental and control groups, including means and standard deviations. The table summarizes baseline group comparability and the direction of changes observed following the intervention.

To analyze intervention outcomes, linear mixed-effects models were used with group (experimental vs. control), time (pre-test vs. post-test), and the Group \times Time interaction included as fixed effects. Because of the clustered study design, school was included as a random effect.

Intraclass correlation coefficients (ICCs) for the outcome variables ranged from 0.04 to 0.11, indicating clustering effects at the school level and supporting the use of multilevel modelling procedures.

A statistically significant Group \times Time interaction was observed for HTKS-R performance. Significant Group \times Time interaction effects were also identified for Walking Backward, Hopping for Height, and Moving Sideways, whereas no statistically significant interaction effect was observed for Jumping Sideways. All statistically significant motor-coordination outcomes remained significant after Bonferroni

correction (adjusted $p < 0.0125$).

Moderate to large Group \times Time effects were observed for Walking Backward, Hopping for Height, and Moving Sideways, whereas Jumping Sideways demonstrated a small and non-significant effect.

The results of the linear mixed-effects models, including estimates for the fixed effects of group, time, and the Group \times Time interaction, as well as associated p-values and effect sizes, are presented in Table 2.

Baseline-adjusted analyses were also conducted using ANCOVA. Post-test scores were specified as dependent variables, group was included as a fixed factor, and pre-test scores were included as covariates.

The ANCOVA results were consistent with the patterns observed in the linear mixed-effects models. Significant group effects were identified for HTKS-R performance, Walking Backward, Hopping for Height, and Moving Sideways after adjustment for baseline performance. These findings indicated higher post-test performance in the experimental group compared with the control group.

No significant group effect was observed for Jumping Sideways according to the ANCOVA results ($p = 0.569$). Detailed ANCOVA results are presented in Table 3.

Table 1. Statistical analysis (mean \pm SD) and comparison of pre-intervention executive-function and motor-coordination variables

Variable	Group	Pre-test (Mean \pm SD)	Post-test (Mean \pm SD)	Baseline p-value
HTKS-R	Experimental	41.69 \pm 1.88	44.95 \pm 2.10	0.118
	Control	41.23 \pm 1.92	41.17 \pm 1.85	
Walking Backward (steps)	Experimental	29.70 \pm 3.90	33.41 \pm 4.10	0.672
	Control	29.97 \pm 3.85	30.03 \pm 3.80	
Hopping for Height (points)	Experimental	16.12 \pm 2.70	22.45 \pm 3.10	0.541
	Control	15.95 \pm 2.65	16.40 \pm 2.80	
Jumping Sideways (counts)	Experimental	36.15 \pm 4.20	36.13 \pm 4.10	0.487
	Control	35.71 \pm 4.30	35.67 \pm 4.25	
Moving Sideways (counts)	Experimental	33.18 \pm 3.75	37.07 \pm 3.95	0.603
	Control	33.45 \pm 3.80	33.31 \pm 3.70	

Note. Data are presented as mean \pm standard deviation. Baseline p-values were derived from independent-samples t-tests

Table 2. Results of the linear mixed-effects models for Group \times Time interaction effects.

Variable	Effect	Estimate (β)	SE	p-value	Partial η^2p	Cohen's d
HTKS-R	Group \times Time	3.18	0.62	<0.001	0.12	0.65
Walking Backward	Group \times Time	3.71	0.85	<0.001	0.10	0.58
Hopping for Height	Group \times Time	6.33	1.05	<0.001	0.14	0.70
Jumping Sideways	Group \times Time	0.02	0.78	0.981	0.00	0.01
Moving Sideways	Group \times Time	3.89	0.92	<0.001	0.11	0.60

Note. β = fixed-effect estimate; SE = standard error; η^2p = partial eta squared. Cohen's d values were calculated from adjusted means. Bonferroni-adjusted significance levels were applied to motor-coordination outcomes ($p < 0.0125$).

Table 3. Results of the analysis of covariance (ANCOVA) adjusted for baseline values.

Variable	Adjusted Mean (Experimental)	Adjusted Mean (Control)	Mean Difference	SE	p-value	Partial η^2p
HTKS-R	44.87	41.22	3.65	0.58	<0.001	0.13
Walking Backward	33.32	30.05	3.27	0.79	<0.001	0.09
Hopping for Height	22.30	16.35	5.95	0.98	<0.001	0.15
Jumping Sideways	36.10	35.69	0.41	0.72	0.569	0.01
Moving Sideways	36.95	33.28	3.67	0.88	<0.001	0.11

Note. Adjusted means represent post-test scores after controlling for baseline (pre-test) values. SE = standard error; η^2p = partial eta squared. Bonferroni-adjusted significance levels were applied to motor-coordination outcomes ($p < 0.0125$).

Improvements were observed in executive function (HTKS-R), Walking Backward, Hopping for Height, and Moving Sideways, whereas no significant intervention effect was identified for Jumping Sideways.

Discussion

In the present study, the effects of participation in a Flanker-based locomotor-training program on executive attention and motor coordination in first-grade students were examined. The findings indicated that cognitive-conflict tasks integrated into a structured locomotor-activity intervention improved HTKS-R performance as well as several aspects of motor coordination, including balance and control during dynamic movements. The findings also contribute to the growing body of literature suggesting that cognitively challenging forms of physical activity may enhance executive function and executive attention, particularly when cognitive and physical tasks are performed simultaneously [28, 29].

The improvement observed in HTKS-R performance reflects enhanced executive attention and behavioral self-regulation during locomotor tasks involving cognitive conflict and response inhibition within the Flanker-based format. Under these task conditions, children were required to follow specific stimulus-response mappings, switch response rules, and suppress automatic responses through continuous monitoring of task-relevant stimuli and motor responses. These task characteristics directly involve core executive processes, particularly inhibitory control and cognitive flexibility.

Previous research has indicated that cognitively engaging physical activities requiring interference control and rule switching may improve executive function in children [9, 30]. In addition, combining physical activity with tasks requiring executive control may produce greater cognitive improvements than physical activity performed without additional cognitive engagement. Task-oriented cognitive demands during motor activity may therefore contribute to improvements in executive function [13, 31].

The differences observed between the experimental and control groups suggest that the improvements were associated with the specific task demands included in the intervention rather than with typical developmental changes or participation in regular physical-education classes.

Across the KTK subtests, improvements in motor coordination were not observed to the same degree, indicating task-specific intervention effects. Significant improvements were identified for Walking Backward, Hopping for Height, and Moving Sideways, whereas Jumping Sideways did not demonstrate significant performance changes. These findings suggest that the Flanker-based locomotor training provided greater benefits for motor tasks requiring dynamic balance, movement control, and continuous adjustment of motor responses.

Previous studies have also reported associations between motor-coordination development, motor-skill performance, and cognitive or behavioral functioning, particularly in tasks involving adaptive control and perceptual-motor integration [32, 33]. In contrast, tasks such as Jumping Sideways emphasize movement speed and repetitive execution over short time intervals and may involve lower levels of executive-control processing relative to more automated neuromuscular movement patterns.

The absence of improvement in Jumping Sideways performance is therefore consistent with the task-specific characteristics of the intervention, which emphasized cognitive-motor integration rather than movement speed. These findings are also consistent with previous research indicating that the inclusion of cognitive demands within motor activities may produce domain-specific effects on motor-performance outcomes [34].

The results of the present study add to the body of evidence demonstrating interactions between executive function and motor coordination in young children, suggesting possible shared underlying processes across cognitive and motor domains. The concurrent improvement in HTKS-R performance and selected motor-coordination tasks supports the idea that executive processes, particularly inhibitory

control and cognitive flexibility, contribute to the regulation of goal-directed movement and adaptive motor behavior [35].

Continuous monitoring, error correction, and movement adjustment represent examples of interactions between cognitive and motor systems during task performance. Previous research has demonstrated associations between executive function and motor skills during childhood, with improvements in one domain often accompanied by improvements in the other [21, 36].

The Flanker-based locomotor training may also be interpreted from a dual-domain perspective because the intervention simultaneously targeted executive-control processes and locomotor coordination. This combination may contribute to more efficient cognitive-motor integration. Such integration may help explain the pattern of results observed in the present study, where stronger effects were identified for motor tasks requiring higher levels of executive control, whereas performance remained relatively unchanged in tasks involving lower executive-control demands.

Overall, the present findings are consistent with previous studies reporting positive effects of cognitively enriched physical activity on executive function and motor performance in children [17, 37]. The current study extends this line of research by applying a structured Flanker-based locomotor framework with predefined stimulus-response mappings, conflict conditions, and progression rules embedded within movement tasks. The integration of cognitive-conflict conditions into locomotor activities may help explain the observed improvements in executive function and selected aspects of motor coordination [29, 38].

Improvements in executive function and motor coordination may reflect partially overlapping cognitive and motor-control processes involved in adaptive behavior. Previous theoretical and neurocognitive research suggests that activation of prefrontal cortical networks may be associated with executive functions, particularly cognitive flexibility and inhibitory control, which contribute to goal-directed behavior and action selection [39].

The basal ganglia and cerebellum are examples of subcortical and motor-related structures that interact dynamically with these neural networks. These structures are believed to contribute to movement coordination and timing, as well as adaptive correction of movement-related errors. Therefore, tasks requiring simultaneous cognitive control and motor execution may involve functional interactions between cognitive and motor processes during cognitively demanding movement activities.

Motor competence and executive function are positively associated throughout childhood development and may involve partially overlapping

functional mechanisms related to frontal and motor brain regions [40]. The present findings may reflect adaptive relationships between executive-control processes and motor performance during cognitively enriched locomotor activities, suggesting that repeated engagement in cognitively demanding movement tasks may be associated with improved cognitive-motor coordination [3, 41].

Many studies have examined the effectiveness of cognitive-locomotor intervention programs for children. These findings suggest that incorporating cognitive challenges during motor tasks may provide an ecologically relevant learning experience that supports adaptive behaviors in both cognitive and motor domains. In addition, the effectiveness of such interventions may depend on how well cognitive demands are aligned with the characteristics of the motor tasks. Differences in intervention structure, cognitive-task complexity, and movement specificity across previous studies may partly explain variations in the magnitude and consistency of reported outcomes.

Limitations and Future Research

Several limitations should be considered when interpreting the findings of the present study. The sample included only first-grade girls attending private schools. Therefore, the findings may not be fully generalizable beyond this population. The relatively short intervention period, limited number of school clusters, and use of complete-case analysis may also limit the broader interpretation of the findings.

In addition, the inclusion of only six school clusters may have reduced the stability of cluster-level variance estimation and increased the possibility of residual school-level confounding despite the use of multilevel statistical procedures.

Future studies should examine the long-term sustainability of these effects across more diverse child populations and incorporate neurophysiological measures to further investigate mechanisms underlying cognitive-motor integration.

Practical Implications

The results illustrate how integrating cognitive components into movement-related activities may support executive function and motor coordination during early childhood. Furthermore, this model provides an example of how an evidence-based approach may be implemented within regular physical-education classes to support cognitive-motor development, academic readiness, and behavioral regulation. However, the practical relevance of these findings should be interpreted in relation to the specific executive and motor demands targeted by the intervention.

Conclusions

The present findings suggest that Flanker-based locomotor training may support improvements in executive attention and selected aspects of motor coordination in young children. Overall, the findings indicate that the integration of cognitive-conflict, response-inhibition, and rule-switching components into structured motor tasks may improve executive attention, as reflected by HTKS-R performance, as well as selected components of motor coordination. These improvements appeared to be task-specific, with greater changes observed in motor tasks requiring higher levels of cognitive control than in tasks involving lower executive-control demands.

The findings also contribute to previous research examining interactions between cognitive and motor activities by providing a structured framework for integrating cognitive demands into locomotor tasks. The Flanker-based locomotor-training approach may provide a structured method for supporting cognitive and motor development through the simultaneous engagement of executive-control and locomotor processes. This study contributes to the growing literature on cognitively enriched physical activity in school settings and may have practical relevance for the design of structured cognitive-motor activities during early childhood education.

Conflict of Interest

The authors declare no conflict of interest.

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