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Original Article

From Reaction to Prediction: Effects of Anticipation-Driven Training on Behavioural Self-Regulation and Reactive Agility in Children

Short title: Anticipation Training in Children

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Abstract

Despite growing evidence, anticipation-based mechanisms remain underexplored in school settings, especially among Arab populations. The purpose of this research study was to determine whether an anticipation-based locomotor training program affected behavioural self-regulation and reactive agility in primary school-aged children, using a cluster-randomised controlled trial design. Of the 338 participants in 10 schools who participated in the study, there were two groups: one group (n = 168) was assigned to the experimental condition, and one group (n = 170) was assigned to the control condition. The experimental group received an 8-week treatment that consisted of three sessions per week, with each session including significantly altered visual and auditory stimulus presentations designed to stimulate predictive processing skills as well as quick decision-making ability under temporal constraints. Behavioural self-regulation was evaluated with the HTKS-R, and reactive agility was measured using a Y-test. Group and time interactions were statistically significant at $p<0.05$, indicating that the experimental group had significantly improved HTKS-R scores and lower measurable reactive agility times than the control group. It appears that embedding anticipatory demands within a structured physical activity may improve children's cognitive-motor performance.

Keywords: predictive processing, perception–action coupling, cognitive–motor integration, response selection, ecological validity.

Introduction

Increasing attention has been directed in recent years to the role of executive functions (EFs) in supporting adaptive functioning and behavioural regulation during childhood. Executive functions (EFs), including inhibitory control, working memory, and cognitive flexibility, are commonly conceptualised as partially separable but dynamically interrelated cognitive processes that support goal-directed behaviour and adaptive performance under changing environmental demands (Diamond, 2013; Miyake et al., 2000). These functions are particularly important during childhood, where they contribute substantially to behavioural self-regulation and adaptive behaviour in cognitively demanding contexts (Ibrahim et al., 2026). Furthermore, current research suggests that executive functioning may be positively influenced when physical activity is performed alongside cognitively engaging task demands. Specifically, movement-based activities involving cognitive engagement, decision-making, and adaptive response demands have been associated with positive contributions to cognitive and behavioural regulation in children, particularly when compared with simple repetitive motor practice (de Greeff et al., 2018; Ibrahim et al., 2026). However, evidence across physical activity interventions remains heterogeneous, with some studies reporting small or non-significant cognitive effects depending on the qualitative characteristics of the intervention and comparison conditions (Vazou et al., 2019). This perspective reflects an increasing recognition that physical activity environments often involve the simultaneous interaction of cognitive, perceptual, and motor processes. Additionally, motor and cognitive development share a common developmental foundation and interact continuously to support behavioural self-regulation (Guimarães et al., 2024).

Although there is increasing interest in combining cognitive activities with physical activity (i.e., enriching physical activities with cognitive demands), most interventions continue to focus on reactive control, where individuals respond only after a stimulus appears. In situations involving temporal constraints and environmental uncertainty, executive functions such as inhibitory control and cognitive flexibility may support the efficient selection and adjustment of goal-directed responses. From this perspective, anticipation-oriented movement contexts may require children to extract, interpret, and integrate early perceptual information in order to prepare adaptive motor responses before complete stimulus emergence. Accordingly, anticipation may contribute to executive functioning not only through response execution itself, but also through proactive response preparation, inhibitory adjustment, and flexible updating of action plans under dynamic task demands (Murphy et al., 2024). The interaction between contextual information and kinematic/temporal properties within dynamic performance environments is part of the process of successfully adapting to changing environments; therefore, evidence supports the assertion that perceptual-cognitive training that emphasises anticipation may enhance response efficiency and accuracy (Zhu et al., 2024). From an ecological dynamics perspective, these adaptive responses may be partly explained through perception-action coupling; the rapid translation of environmental cues into goal-directed movement represents an important component of agility in real-world environments, rather than relying solely on pre-planned motor execution (Zhao et al., 2026). Nonetheless, despite the compelling evidence for these anticipatory demands, they are not adequately incorporated into structured physical activity programs for children, especially in the school environment.

Regarding functionality, self-regulation of behaviour is an expression of executive functions in real-life situations and the ability to regulate one's actions toward achieving a goal and the requirements of the task. The assessment of this concept has generally taken place using performance-based measures that involve the combination of the three processes of executive function (e.g., inhibition of behaviour, working memory, and cognitive flexibility) when providing a structured motor response, such as the Head-Toes-Knees-Shoulders Revised

(HTKS-R) task. The HTKS-R task provides an example of this combination of processes by requiring both the inhibition of pre-determined or automatic responses (i.e., Head-Toes) and the adaptation of one's response based on changing rules (i.e., stretching and twisting in various directions) under progressively increasing levels of cognitive load (Gonzales et al., 2021; McClelland et al., 2021).

Simultaneously, reactive agility suggests that there is a perceptual-motor dimension of performance wherein rapid detection of stimuli, efficient decision-making within time constraints, and completion of movement occur instantly. Reactive agility is substantially influenced by cognitive processes, such as anticipation and choice of response (Zhao et al., 2026). Pre-planned movements do not include this continuous integration of perceptual information and motor output (i.e., performance) during reactive agility as would a pre-planned movement; therefore, many behaviours related to both self-regulation of individual behaviour and reactive agility will be affected by similar processes associated with executive function and anticipation that could be evaluated through an integrated and cognitive-motor lens.

Nevertheless, there are a number of substantial gaps in terms of how to use those findings to design effective interventions. The current approaches primarily focus on general cognitive engagement, and there is no direct focus or targeting of the underlying mechanisms that drive adaptive behaviours when people are under time pressure. Anticipatory mechanisms, in particular, are insufficiently defined and inconsistently operationalised in structured physical activity programs; however, they may influence how speed and accuracy are regulated during rapid responses.

A number of studies have looked at the relationship between executive functions and the motor performance of the individual; however, there has been minimal use of a unified cognitive–motor framework that considers the demands of actual tasks that require both cognitive and physical processing. This is particularly clear in the case of reactive agility. Reactive agility relies on the dynamic coupling of perception, decision-making, and movement execution.

Another limitation of existing research involves the lack of representation of female participants in cognitive-motor intervention studies. Research has consistently shown that girls have lower physical activity levels and experience more obstacles to participating than boys (Arumi-Prat et al., 2025; Kretschmer et al., 2023). Despite this difference, the majority of studies involving interventions have used mixed or male-dominated participant samples and have not placed emphasis on girls as their primary participants. This gap is especially relevant in educational settings where there are different levels of participation available for boys and girls, as well as in Middle Eastern settings such as Iraq.

These findings point to a clear need for ecologically valid interventions that incorporate anticipatory mechanisms and integrate executive function with perceptual-motor performance in an integrated way; this gap needs to be filled to advance theoretical understanding as well as allow for the creation of inclusive, context-sensitive approaches that reflect the cognitive and environmental demands placed upon children.

In the present study, we developed an anticipation-driven locomotor training approach designed to integrate anticipatory processing into structured physical activity tasks, rather than relying solely on general cognitive engagement during movement performance. The intervention systematically manipulated visual and auditory stimuli, movement timing, and response demands in order to encourage early information extraction, predictive processing, and adaptive action preparation under time constraints.

The study was designed within an integrated framework that simultaneously examines behavioural self-regulation and reactive agility. This framework enables the simultaneous assessment of executive control and perceptual-motor performance within a single ecologically valid context. Furthermore, the goal of the study, which focuses on young schoolgirls, is to help address the under-representation of female participants in cognitive-motor intervention studies and will additionally provide insight into how schools provide different opportunities for males and females, especially in countries such as Iraq.

Collectively, these gaps highlight the need for mechanism-oriented cognitive-motor interventions examined within under-represented populations and ecologically valid school settings. Utilising these gaps in the literature, the current study examined the efficacy of an anticipation-driven locomotor training program (OD) on behavioural self-regulation and reactive agility among primary school students through a cluster randomised controlled study design. The intervention was specifically designed around visually and auditorily presented stimuli requiring early extraction of information, predictive processing, and rapid decision-making under time constraints, which were intended to engage processes involved in adaptive cognitive-motor performance.

It was hypothesised that children exposed to the anticipation-driven training would demonstrate significantly greater improvements in behavioural self-regulation, as assessed by the HTKS-R, compared to those receiving standard physical education. In addition, the experimental group was expected to exhibit superior gains in reactive agility, which may be associated with more adaptive perception–action coordination and response selection in dynamic environments. Finally, it was hypothesised that these improvements would be consistent with the integration of executive control and perceptual–motor demands targeted within the anticipation-based training approach under cognitively and temporally demanding movement conditions.

Method

Study Design

The study was designed as a two-arm, pre/post cluster-randomised controlled trial to examine the effects of an anticipation-based locomotor training program on behavioural self-regulation and reactive agility in children attending primary school. Schools were randomly assigned as the unit of analysis in order to minimise contamination between subjects in the same primary school setting.

Two study branches (the study group and the control) were included in the study. Schools were used as clusters, and the two schools were assigned to receive either the study or control groups via cluster-level random selection. The use of cluster randomisation improved the viability of the ecological validity of the school-based setting and limited the amount of exposure from an intervention component to different groups of students. Outcome measures were taken during pre-intervention (baseline) and immediately following the 8-week intervention period to allow for a determination of whether or not there were any differences in performance outcomes between groups over time.

This research study aimed at not only evaluating effects from the intervention, but also determining if what was observed as change could be attributed to an enhanced ability of anticipatory-processing mechanisms to work differently than what would be expected from an increase in the amount of physical activity. To help support valid causal inferences (such as anchoring or anchoring-and-adjusting), there was alignment between the unit of randomisation (school level) and the statistical framework for analysis.

The experimental group received a structured anticipation-based training regimen that was incorporated into the regular physical education program, while the control group used the standard physical education program without any cognitive enrichment or cognitively driven tasks. The two groups were provided comparable amounts of time and opportunity for participation (number of sessions and session length) so that if the two groups experienced any difference in their performance on the outcome measure, it could be attributed to the intervention type rather than differences in training exposure.

Participants

Participants in this research study came from a total of 10 different all-girls' private primary schools in Samara, Iraq, that included only one class of second grade per school. The study employed a census sampling method, meaning that all eligible students in all the schools were considered for participation. The research was conducted during the first semester of the 2025–2026 academic year.

A group of 373 students was screened initially; however, only 351 students met the criteria required for inclusion in the baseline assessment. The enrollment criteria were that children needed to be enrolled in the second grade, have regular attendance in PE classes, and provide written informed consent through their parents/legal guardians for inclusion in the baseline assessment of students. As part of the intervention, 13 students were lost to follow-up due to absence from PE classes or withdrawal from the study, resulting in an analytical sample of 338 students remaining in the final analytical sample. All of the remaining subjects completed both pre- and post-intervention assessments and were included in the final data analysis.

The pattern of participants flowing through all phases of the study (screening, determining eligibility, assigning participants to groups, following participants, and analysing participant data) was captured as per the CONSORT guidelines for cluster randomised trials (Campbell et al., 2012). Participants were excluded from the study if they had any medical or physical conditions that would limit their ability to participate in physical activity, and/or if they were not present for the baseline assessment; did not complete consent procedures, or could not follow the established protocols for the administration of the HTKS-R.

In combination with the characteristics of participants (e.g. their age), specific information about their height, weight and waist circumference were collected, following standardized protocols, for example, recording their age through official educational records, weighing them using a well-calibrated digital scale in standard dress, and weighing them with no shoes are meant to provide the basis for establishing comparability between groups, so that they can be compared (to each other) on the basis of how they were selected.

Ten schools were randomly and sequentially assigned either to be part of the experimental group (five schools) or the control group (five schools) using a computer-generated random order created by an unfamiliar researcher not associated with the data collection and outcome processing. This method is called cluster randomisation, whereby the schools were chosen to be the units of allocation in this study.

The final distribution of participants was as follows: experimental group (n = 168; cluster sizes: 32, 34, 32, 34, and 36) and control group (n = 170; cluster sizes: 34, 32, 36, 36, and 32).

Although the study employed a census-based recruitment strategy by including all eligible participants from the available schools, an a priori sample size justification was also considered to support the planned analyses. The final analytical sample included 338 participants distributed across 10 school clusters, with an average cluster size of approximately 34 participants per school. Given the observed cluster structure and the use of linear mixed-effects models accounting for school-level clustering, the available sample was considered adequate to detect intervention-related effects under conventional statistical assumptions ($\alpha = 0.05$; power = 0.80).

Statistical testing appropriate for comparison between groups was performed on baseline measurements to establish comparability of baseline variables across groups before initiation of the intervention program using appropriate statistical tests (for all comparisons with baseline demographics and anthropometrics). All Participants were Female Students. Prior to conducting assessments, parental consent and/or school permission was obtained.

Prior to the study's initiation, approval for ethical conduct was obtained from the University of (xxx) (Approval Number 20, dated March 2, 2025); all study procedures also adhered to the Declaration of Helsinki, and written informed consent was acquired through the use of written forms that were signed by parents/guardians before they allowed their children to participate in the study.

Measures

Behavioral Self-Regulation

The Head-Toes-Knees-Shoulders-R (HTKS-R) is a standardised performance-based measure intended to measure executive functioning in young children in relation to behavioural self-regulation. The measurement of inhibitory control, working memory, and cognitive flexibility occurs through motor responses that are structured around given directions (Gonzales et al., 2021).

The activity asks kids to perform an action in the reverse of what they would normally do with an instruction (e.g., touching their toes when told to touch their head) and is designed to engage kids' ability to inhibit their responses as well as their cognitive flexibility in an immediate way; as the tasks become more complex, the child will need to remember multiple rules/ways they can respond and utilize those remembered rules based on their current situation; this example demonstrates the interconnectedness of all areas of executive functioning.

According to Gonzales et al. (2021), previous validation studies indicate that the HTKS-R has good internal consistency, inter-rater reliability, and construct validity within a variety of populations. Additionally, the HTKS-R has been found to have predictive validity with regard to academic success and larger executive functioning outcomes (McClelland et al., 2021).

One-on-One Administration of the Assessment: All assessments were administered one-on-one in quiet classrooms in accordance with the previously outlined protocols. To ensure that participants understood the nature of the tasks, each participant received practice task trials prior to being given the testing tasks. All tasks had additional increasing complexities in the rules of those tasks, as participants progressed through the sections of the tasks. Using a standardised scoring system (0 = incorrect; 1 = self-corrected; 2 = correct), all participants received an overall task score of 0 to 118. The average participant score was approximately 5- 6 minutes.

Because repeated administration of performance-based executive function measures may introduce practice-related improvements, standardised instructions, identical administration procedures, and structured practice trials were provided at both assessment points. In addition, the inclusion of a control group assessed at the same time intervals helped ensure that any practice effects associated with repeated testing would be similarly distributed across groups, thereby reducing their potential influence on between-group comparisons.

Moreover, recent empirical studies done in Iraq have supported the use of HTKS-R for detection of behavioural self-regulatory change related to intervention in Arab educational settings (Ibrahim et al., 2025).

Reactive Agility

A Y-shaped reactive agility test was used to assess reactive agility. The purpose of the reactive agility test was to assess how well an individual can respond to an unpredictable visual stimulus with a change of direction. Reactive agility is defined as the speed at which an individual can perform a whole-body movement in response to a visual stimulus; this involves integrating perceptual, decision-making, and motor execution processes (Young et al., 2001).

Modern agility models emphasise that an individual performs because of how they perceive and make decisions rather than through just executing a movement that was planned (Young & Farrow, 2006). Additionally, reactive agility differs from change of direction speed and is a more accurate representation of actual situations regarding both types of agility.

Reactive agility testing is based on research that has been proven to contain empirical data that illustrates its ability to differentiate between different performers and show how perceptual-motor integration can be measured (Sheppard & Young, 2006). Further, reactive agility testing has also provided evidence that perceptual and decision-making components of agility can be trained and improved, leading to improved overall performance results (Serpell et al., 2010).

The study's test was completed from a common starting point where participants were given instructions to run to 5m in a straight line and perform a change of direction 45° to the left or right, depending on the visual cue, from the finished line (Sheppard & Young, 2006). The test itself was based on why a source of motion needed to be created in order to measure a quick response to the change of the environment while performing one of the many various types of activity.

Each participant began from a standard starting position about half a meter behind the starting line while the directional stimulus was presented at that time as part of the movement initiation. Thus, the participant had to rapidly couple perception and decision-making. Each participant performed a total of three trials to obtain their fastest valid trial (used for analysis purposes). The directional cue was presented unpredictably at movement initiation, requiring an immediate perception–decision–action response. All participants had trial runs prior to testing to familiarise themselves with the task. The total response time (in sec) was measured from the onset of the stimulus until the completion of the task.

On average, the testing duration for an individual participant was 2 or 3 minutes for both familiarity and valid responses. Only valid responses will be included when evaluating participant performance, as it demonstrates perceptual-motor integration and eliminates the impact of censoring incorrect responses (e.g. due to lack of familiarity) on variability in the measurement of accuracy.

The test was administered under standardised conditions across all participants, ensuring measurement consistency and reliability.

Intervention Program

The experimental group was assessed for their participation in an anticipatory-based locomotor training intervention that focused on improving the use of predictive processing, perceptual-motor integration, and executive control. The intervention occurred for eight weeks with three training sessions, each lasting approximately 40 minutes, in indoor physical education.

The primary researcher, who is a qualified physical educator, delivered the intervention, assisted by trained aides who presented stimuli and managed the stations according to standardised operating procedures for configuration of visual and auditory cues at all stations. Recruitment of participants for small group participation was done in such a way as to systematically provide the participants with the opportunity to rotate between the stations in order to allow for continuous monitoring and to allow for controlled administration of task requirements on an ongoing basis for the duration of each intervention session.

The 30-minute main activity is divided into eight different stations (3 minutes each), where an approximate number of four students is assigned to work for three minutes on each station. Each student then rotates to the next station at the end of the three minutes, resulting in completing a full rotation through all eight stations during one session. This was situated between a warm-up and cool-down period that took five minutes each.

As part of the process of making tasks progressively more difficult throughout the intervention, three key stimulus variables were manipulated: (1) clarity (clearly understood versus ambiguity of the signals presented), (2) temporal predictability (the use of predictable timing versus the use of delayed or irregular timing), and (3) response congruence (the difference between congruent v. conflicting stimuli). The progression of challenge was maintained on a consistent basis across all task stations in order to provide a structured challenge to the skills of anticipatory processing, the ability of cognitive flexibility and the skills of inhibitory control under time constraints.

Each station was designed to engage perceptual-cognitive processing and executive function demands. Task activities required anticipatory decision-making, inhibitory control, and rapid response selection under time constraints. Collectively, the station design aimed to promote efficient information processing, adaptive response selection, and accurate movement under progressively challenging task conditions while supporting the integration of anticipatory processing and perceptual-motor coordination.

All stations incorporated visual stimuli (e.g., directional arrows, colored markers, and instructor-generated signals) and auditory cues (e.g., hand claps and whistle signals). These stimuli were systematically manipulated in terms of clarity, timing, and congruency to provide progressively increasing task demands. A visual overview of the intervention structure, including locomotor tasks, stimulus characteristics, cognitive demands, and executive function components, is presented in Figure 1.

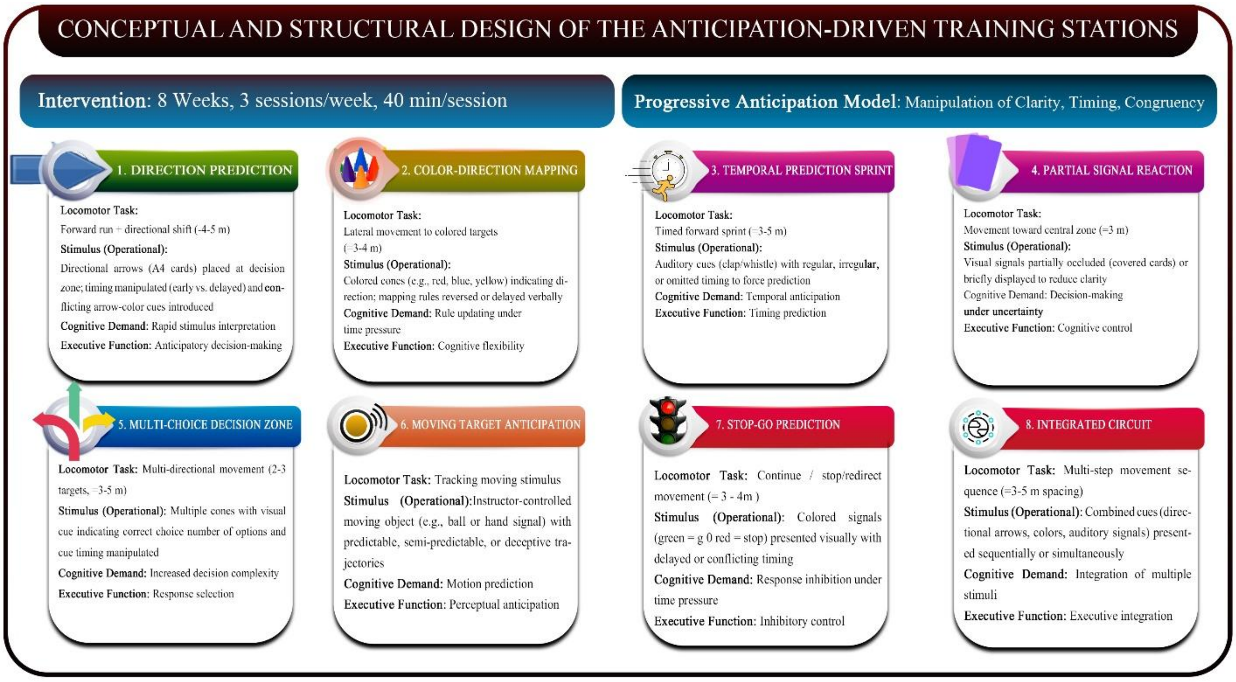

Figure 1. Conceptual and structural design of the anticipation-driven training stations, illustrating locomotor tasks, stimulus characteristics, cognitive demands, and executive function components across progressively structured task conditions.

Table 1. Summary of the Anticipation-Driven Locomotor Training Program.

Component	**Description**
Program duration	8 weeks
Session frequency	3 sessions per week
Session duration	40 min
Warm-up	5 min
Main activity	30 min
Cool-down	5 min
Number of stations	8 stations
Participants per station	Approximately 4 participants
Station duration	3 min per station
Rotation format	Participants rotated sequentially through all stations
Stimulus modalities	Visual (directional arrows, colored markers, instructor-generated signals) and auditory (hand claps and whistle signals)
Progression variables	Stimulus clarity, temporal predictability, and response congruency
Executive function demands	Inhibitory control, cognitive flexibility, anticipatory decision-making, and response selection
Intended cognitive-motor processes	Predictive processing, anticipatory processing, perceptual-motor integration, and adaptive action preparation

Note. The table summarises the core structural characteristics of the intervention. Detailed descriptions of individual stations are provided in Figure 1.

The practical application of all stations was via materials that can be found in any indoor school hall (standardised). Visual stimuli were displayed using cones, directional arrows on laminated A4-sized cards, and floor markers spaced between 3 and 5 meters from the start.

When colour-direction mapping was required, distinct colours marked movement direction (e.g., red, blue, yellow), and the instructor provided verbal instructions regarding the rules to be used to complete the task.

Auditory cues, such as a clap of the hands or a whistle, were used to manipulate timing and control when a person could begin their actions or move. The use of delayed or unpredictable stimuli was achieved through varying cue timing based on when they were presented relative to the time the movements occurred. In addition, for tasks that required the use of partial or ambiguous signals, visual cues were intentionally occluded (i.e., cards partially covered) or displayed for short periods of time to limit perceptual clarity.

The instructor used manual control over the direction or timing of visual signals to create predictable or unpredictable movement patterns, depending on whether the tasks were to be anticipated or targeted. Visual signals (coloured) were presented as stop (red) or go (green), with a delay on the go signal to present stop-go tasks and increase the need for inhibition during this type of exercise.

The layout of each station was arranged so that groups of approximately four participants could rotate through each station every three minutes. Each station required a total working surface area of approximately 3— 5 m for each participant, which would have made the total required surface area feasible within a typical school gymnasium. This arrangement enabled all stations to be set up and implemented consistently, thus allowing for clear, replicable results with stations that were both ecologically valid and practically applicable in actual classroom settings.

Standardisation and Fidelity

Standardised drawings, station layouts, and instructional procedures were used across all schools. Prior to participation, all children received demonstration trials to ensure task understanding. Task complexity progressed in line with predefined weekly guidelines, and intervention delivery was supervised by the primary researcher to ensure consistency across sessions and schools. Fidelity was monitored using session logs and structured checklists, with adherence levels maintained above 80% throughout the intervention period.

Control Group

The control group participated in the regular school physical education program, consisting of running activities, basic games, and free play, without structured anticipatory or cognitively demanding movement tasks. Physical education teachers continued their usual instructional practices and were not involved in delivering the experimental intervention.

Because of the study design, neither participants nor instructors could be blinded to their group assignment. Although outcome assessments were completed with conditions held constant, evaluators could not be blinded to group allocation.

Statistical Analyses

Analyses were performed using IBM SPSS Statistics (version 26.0). Descriptive statistics were calculated, and mean and standard deviation (M ± SD) were reported as middle-range continuous variables.

Using independent-samples t-tests, the baseline comparability between the experimental and control groups was evaluated for each continuous variable: Age, Body mass, Behavioural Self-Regulation (HTKS-R), and Reactive Agility. In addition to conducting statistical significance testing, standardised effect sizes (Cohen's d) were computed to quantify the magnitude of difference between groups at baseline. This dual approach was employed to provide a more robust evaluation of initial group equivalency than using p-values alone.

Linear mixed-effects models (LMMs) were used to conduct the initial analysis and account for clustering in the data. The independent variables (IVs) include the fixed effects of group (experimental versus control), time (pre-intervention versus post-intervention), and the interaction between group and time. The random intercept for school will account for variability between clusters to obtain valid standard error estimates, given the use of a cluster-randomised design. The group × time interaction variable was examined as the primary measure of the influence of the intervention.

The Intraclass Correlation Coefficient (ICC) was computed using Mixed Effects Modelling to assess how much of the variance was attributable to clustering, specifically at the school level. This statistic quantified how much of the variance in responses among participants who clustered together was attributable to cluster membership, thereby supporting the use of multilevel models for the data.

As a sensitivity analysis, supplementary analyses were conducted using analysis of covariance (ANCOVA), with post-intervention scores as the dependent variable and group (experimental vs control) as the fixed factor. The baseline values of the respective outcomes were added as covariates to account for any baseline differences. Age and body mass were also entered as covariates to control for potential confounding effects from variations in growth and physical characteristics.

To quantify the magnitude of differences between groups, we used Cohen's d effect sizes. Effect sizes were interpreted using conventional guidelines, with values of approximately 0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively. Reporting effect sizes alongside statistical significance provides a broader perspective on the practical importance of the intervention effects.

The assumptions of normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene's tests, respectively. To conduct these statistical analyses, these assumptions were reasonably met, owing to the robustness of parametric analyses for sufficiently large sample sizes. Missing data comprised only a small portion of the total data collected and were handled using a complete-case analysis. Only participants with complete data for all outcomes or who attended at least 80% of the intervention were included in the final analysis to ensure high-quality, consistent data; thus, a per-protocol approach was used for the analyses. Given the low attrition rate and the availability of complete outcome data for the final analytical sample, a per-protocol approach was considered appropriate for evaluating intervention effects.

To obtain adjusted group means using mixed-effects modelling, estimated marginal means (EMMs) were estimated from the model covariates and clustering effects, and used to calculate pairwise comparisons between the groups at post-intervention based on the adjusted estimates. Confidence intervals and p-values for each pairwise comparison are also reported to aid interpretation of differences between groups.

Results

The linear mixed-effects models revealed a significant group × time interaction for both behavioural self-regulation and reactive agility ($p < 0.05$).

To help interpret the interaction in this study, descriptive statistics for all study variables from pre- and post-intervention assessments are presented in Tables 2 and 3. The experimental group exhibited greater improvements than the control group in both behavioural self-regulation and reactive agility. Baseline equivalence between the randomised groups was examined across demographic, anthropometric, and performance characteristics prior to the intervention. Therefore, the experimental and control groups were reasonably assessed as equivalent prior to administering the program(s) based on demographic, anthropometric, and performance characteristics.

At baseline, there were no statistically significant differences between the two groups (experimental and control) for demographic and anthropometric characteristics. For example, age did not differ statistically between groups (experimental: M = 7.23 years; SD = 0.18; control: M = 7.24 years; SD = 0.18; p = 0.770). The effect size of this difference was too small to be considered clinically significant (Cohen's d = −0.03). There were also no statistically significant differences between the groups with respect to body mass (experimental: M = 24.87 kg; SD = 2.91; control: M = 25.02 kg; SD = 2.95; p = 0.653) or height (experimental: M = 121.36 cm; SD = 4.12; control: M = 121.58 cm; SD = 4.25; p = 0.639). Again, these differences were too small to be clinically significant (d = −0.05).

There were no significant differences between experimental and control groups based on baseline outcome measures. The two groups had similar behavioral self-regulation scores (HTKS-R), experimental (M = 46.82, SD = 3.58) and control (M = 46.94, SD = 3.51) group scores; there were also no significant between-group differences on reactive agility performance at baseline (experimental mean time = 5.61 seconds, SD = .27; control mean time = 5.60 seconds, SD = .26), and trivial effect sizes. Thus, results indicate that both groups were equivalent on these major outcome measures before this intervention was administered.

Table 2. Baseline characteristics of the experimental and control groups (Mean ± SD).

Variable	Experimental (n = 168)	Control (n = 170)	t-value	p-value	Cohen's d
Age (years)	7.23 ± 0.18	7.24 ± 0.17	-0.29	0.770	-0.03
Body mass (kg)	24.87 ± 2.91	25.02 ± 2.95	-0.45	0.653	-0.05
Height (cm)	121.36 ± 4.12	121.58 ± 4.25	-0.47	0.639	-0.05
HTKS-R (pre)	46.82 ± 3.58	46.94 ± 3.51	-0.33	0.741	-0.03
Reactive agility (s)	5.61 ± 0.27	5.60 ± 0.26	0.31	0.758	0.04

Note. Values are presented as mean ± standard deviation (SD). Baseline comparability between groups was assessed using independent-samples t-tests. Cohen's d was calculated to estimate the magnitude of between-group differences.

Descriptive statistics for the pre- and post-intervention assessments demonstrated a clear trend of increased improvement on behavioural self-regulation (HTKS-R) scores in the experimental group and a similar trend of decreased time to complete tasks using reactive agility in the experimental group compared to the control group. In the case of HTKS-R scores, the experimental group showed a large increase in mean scores from baseline to post-intervention, whereas the control group showed only slight increases over the same period. A similar pattern of decreased completion time with reactive agility was observed in the experimental group, indicating improved performance, while completion times remained fairly stable in the control group.

Table 3. Descriptive statistics for behavioural self-regulation and reactive agility across pre- and post-intervention assessments (Mean ± SD).

Variable	Time	Experimental (n = 168)	Control (n = 170)
HTKS-R	Pre	46.82 ± 3.58	46.94 ± 3.51
HTKS-R	Post	56.47 ± 2.12	46.88 ± 3.55
Reactive agility (s)	Pre	5.61 ± 0.27	5.60 ± 0.26
Reactive agility (s)	Post	4.71 ± 0.30	5.54 ± 0.28

Note. Values are presented as mean ± standard deviation (SD). Lower values in reactive agility indicate better performance.

For both outcome variables, results from the linear mixed-effects models (LMMs), with a random intercept for school to account for clustering, indicated a significant group × time interaction, whereby the experimental group showed a differential change over time compared to the control group. With respect to behavioural self-regulation (HTKS-R), the Group × Time Interaction Effect was statistically significant, and the experimental group demonstrated a large improvement compared with the control group following the implementation of the intervention. Similarly, a statistically significant Group x Time Interaction Effect was observed on Reactive Agility, with the experimental group exhibiting a significant decrease in completion time compared to the control group.

The ICCs showed that a modest proportion of variation was due to clustering effects at the school level, thus supporting the use of a multilevel modelling approach.

Table 4. Linear mixed-effects model results for behavioural self-regulation and reactive agility, including group × time interaction effects.

Outcome	Effect	β	SE	95% CI	p-value	ICC
HTKS-R	Group × Time	9.62	0.41	8.81 to 10.43	< 0.001	0.06
Reactive agility (s)	Group × Time	-0.83	0.05	-0.93 to -0.73	< 0.001	0.05

Note. β = regression coefficient; SE = standard error; CI = confidence interval; ICC = intraclass correlation coefficient. The group × time interaction represents the intervention effect. Negative values for reactive agility indicate improved performance.

Estimated marginal means (EMMs) derived from the mixed-effects models further supported the magnitude and consistency of the observed group differences at post-intervention. Adjusted mean values for both behavioural self-regulation and reactive agility are presented in Table 5. Pairwise comparisons based on these adjusted estimates confirmed statistically significant differences between the experimental and control groups.

Table 5. Estimated marginal means (EMMs) for post-intervention outcomes derived from linear mixed-effects models.

Outcome	Group	Adjusted Mean	SE	95% CI
HTKS-R (post)	Experimental	56.41	0.16	56.09 to 56.73
HTKS-R (post)	Control	46.92	0.17	46.58 to 47.26
Reactive agility (s)	Experimental	4.72	0.02	4.68 to 4.76
Reactive agility (s)	Control	5.53	0.02	5.49 to 5.57

Note. Estimated marginal means (EMMs) were derived from linear mixed-effects models adjusting for clustering at the school level. SE = standard error; CI = confidence interval. Lower values in reactive agility indicate better performance.

Additional analyses using analysis of covariance (ANCOVA) were conducted to further examine group differences at post-intervention while adjusting for baseline values and potential confounding variables. The results remained fully consistent with the primary mixed-effects model findings, indicating significant differences between the experimental and control groups in both behavioural self-regulation and reactive agility after controlling for baseline scores, age, and body mass.

Effect sizes (partial η^2) were interpreted alongside F-values to provide an estimate of the magnitude of the group effect.

Table 6. Analysis of covariance (ANCOVA) results for post-intervention outcomes, adjusted for baseline values, age, and body mass.

Outcome	F	p-value	Partial η²
HTKS-R (post)	482.15	< 0.001	0.59
Reactive agility (post)	421.38	< 0.001	0.56

Note. ANCOVA models were adjusted for baseline values of the respective outcomes, age, and body mass. Partial η² represents the effect size for the group effect after adjustment. Lower values in reactive agility indicate better performance.

To further quantify the magnitude of between-group differences at post-intervention, effect sizes were calculated using Cohen's d. A very large effect size was observed for behavioural self-regulation (HTKS-R) ($d = 3.25$), indicating a substantial improvement in the experimental group relative to the control group. Similarly, a very large effect size was observed for reactive agility ($d = -2.86$), indicating a marked reduction in completion time in the experimental group relative to the control group. These large effect sizes should be interpreted in the context of the relatively low within-group variability, the homogeneous characteristics of the sample, and other methodological factors discussed later in the manuscript.

Discussion

This study used a cluster-randomised controlled design to evaluate the impact of an anticipation-based locomotion training program on primary students' behavioural self-regulation and reactive agility. The results showed that the experimental group demonstrated statistically significant greater improvements than the control group for both dependent variables (self-regulation and agility). Multiple analytical approaches (mixed models, adjusted means and covariance analyses) were used to support the findings. These findings were further strengthened by the use of a cluster-randomised controlled design and multilevel statistical analyses, which enhanced internal validity while preserving ecological validity within real-world school settings. It is particularly noteworthy that the magnitude of the observed changes suggests that incorporating anticipatory and cognitively enriched task demands within physical education settings may contribute to improvements in executive-function-related and perceptual–motor outcomes in children. This is consistent with much of the prior work supporting the positive influence that cognitive engagement during physical activity has on children's executive functioning development and motor performance (Best, 2010; Ibrahim A et al., 2026).

The improvement noted in children's ability to self-regulate (HTKS-R) can be explained by the cognitive requirements of the anticipation-driven training tasks. Each of the intervention tasks had children continually processing dynamic stimuli, suppressing prepotent responses, and re-adjusting a plan of action in a rapidly changing environment. The characteristics of these tasks aligned with the fundamental elements of executive functioning, including but not limited to inhibitory control and cognitive flexibility. Physical activity tasks that include cognitive activity (e.g., inhibiting a response; switching rules; discriminating among stimuli) have been shown to improve executive functioning in children (Diamond & Ling, 2016; Lakes & Hoyt, 2004). With this in mind, it is likely that the combination of anticipatory and decision-making constructs within this intervention played a significant role in improving children's self-regulation skills.

In the present study, improvements in reactive agility can be attributed to how the training tasks have created increasing levels of demand by integrating perceptual and decision-related tasks. Reactive agility relies on an individual's ability to detect relevant environmental cues, interpret them rapidly, and generate appropriate responses under time constraints. In this particular study design, variations in the stimulus timing, clarity, and congruity allowed for systematic manipulation of the task difficulty throughout 8 weeks of training and should have helped the participants process task-relevant information more efficiently and use that information to make appropriate decisions (i.e. produce appropriate motor responses). This explanation is supported by other recent evidence which suggests that decision-making time with respect to dynamic contexts may be enhanced by using anticipation-based training (Wang et al., 2025). Prediction-oriented training protocols have been associated with improvements in visual information processing and response efficiency in dynamic task environments (Xie & Ge, 2026). Thus, the observed improvements in reactive agility may reflect adaptations in processes related to response selection and perceptual-motor performance rather than changes in physical speed alone.

The current intervention likely benefited from the emphasis on anticipatory processing, which was a major component of training. In contrast to traditional physical education activities primarily focused on the execution of motor skills, the current intervention involved generating predictions, interpreting incomplete information, and modifying responses on the fly. Moving from reactive control to predictive control is an essential component of effective movement in dynamic environments, as successful movement often depends on anticipating future events rather than responding only to ongoing events. With the progressive manipulation of stimulus timing, clarity, and congruency, participants were exposed to increasing information-processing demands that may have encouraged the use of more adaptive task-related response strategies. Anticipation, attention to relevant cues, and rapid processing of information are the key perceptual cognitive skills that provide optimal decision-making and motor performance for dynamic performers (Kittel et al., 2024; Wu et al., 2025). Research indicates that using training environments with variations in both time and type of stimuli helps individuals learn how to find task-relevant cues quicker; thus allowing them to choose their response quicker under pressure (Faubert & Sidebottom, 2012). Based on this research, it is likely that the structure of this intervention created an environment that enhanced immediate task performance and reduced time to completion by improving the efficiency of how perceptual–decision processes influence both behavioural self-management and reactive agility, which is consistent with the degree and consistency of change found in the present results.

The present findings add to the growing body of literature that suggests physically active conditions that include cognitive components, or enrichment, are capable of producing significant positive effects on executive-functioning and motor skill performance in children. Researchers have also documented that physical activity interventions with cognitive components—e.g., making decisions, exercising inhibitory control, adapting to environmental stimuli—are more effective at enhancing executive functions than those with only traditional physical activity (Diamond & Ling, 2016; Schmidt et al., 2017). Moreover, a meta-analysis reported evidence indicating that structured physical activity interventions generally can exert positive effects on executive function and attention span in children, especially when cognitive engagement is part of a movement task (de Greeff et al., 2018). The effect of the intervention in the present study, however, appears to be larger than most of the previous intervention studies. The structure and progressive approach of this program's Anticipatory Processing Training was designed to use systematic manipulation of stimulus characteristics to provide a continuous functional challenge for the perceptual and cognitive systems. Unlike other interventions that incorporate cognitive components globally or haphazardly, this program explicitly targets anticipatory processing as a core mechanism for producing both behavioural self-regulation performance outcomes and reactive agility outcome improvement. Other research indicates that children's motor performance is diminished when there is less involvement in an active movement context (Ibrahim et al., 2019).

An additional consideration relates to the potential influence of a novelty effect. Because the intervention introduced a structured and progressively challenging activity format that differed from regular physical education experiences, it is possible that part of the observed improvement was influenced by increased engagement or motivation associated with exposure to a new learning environment. Although the consistency of improvements across outcome measures suggests that the intervention may have produced meaningful effects, the potential contribution of novelty-related influences cannot be completely excluded and should be considered when interpreting the findings.

Factors related to methodology and measurement should be considered when interpreting the very large effect sizes found in the present study. First, the relatively low variability among individuals in the sample may have led to the larger observed effect sizes. The greater homogeneity of samples leads to greater standardised means because of less dispersion in how the participants perform at baseline (Fritz et al., 2012). Second, the limited variability of baseline scores on the reactive agility test may have also arisen partly from the way that reactive agility was assessed. Short duration times used to measure reactive agility effectively result in some limitation on the absolute numerical differences that can occur, because the temporal scale of the test constrains the absolute difference in performance outcome scores. As previously stated, performance on reactive agility tasks is largely the result of perceptual and decision-making processes and not solely physical speed; therefore, the complexity involved in these tasks adds to the likelihood of finding large effects on the reactive agility tasks (Sheppard & Young, 2006). In addition, study findings indicate that you can observe small (more subtle) changes in perceptual-motor coordination and change your level of performance through reaction time (RT) or rapid stimulus-response measurements by training for a period of time (Young et al., 2015). Second, the intervention implemented in the present study was highly specific and systematically structured, consistent with evidence indicating that structured and task-oriented motor skill interventions are effective in enhancing motor competence and related performance outcomes in children (Logan et al., 2012). Third, because both HTKS-R (and reactive agility time) measures can detect shortterm changes in performance based on their responsiveness to change, they are expected to reliably measure significant increases as a result of cognitively engaging interventions (Diamond & Ling, 2016). Thus, the potentially substantial effect sizes found in this study may be the result of both true effects of the intervention as well as the methodological characteristics associated with samples that were compared on a single scale and measures that provided responsiveness to change.

The current results suggest that the observed improvements may be related to the structured nature of the intervention and its emphasis on responding to progressively challenging stimulus conditions. Because anticipatory processing, perceptual–cognitive efficiency, and perception–action coupling were not directly measured, the potential contribution of these mechanisms should be considered inferential rather than definitively established. Nevertheless, the intervention was intentionally designed to incorporate task characteristics theoretically associated with these processes, which may have contributed to the observed improvements in behavioural self-regulation and reactive agility.

Limitations

A number of limitations should be taken into account while assessing this study, including the fact that only female students from private primary schools were sampled from one area of the state. Thus, results may not apply to males or students from different socioeconomic or cultural backgrounds. In addition, socioeconomic status and baseline physical activity levels were not directly assessed and therefore may have influenced the observed outcomes. Furthermore, the exclusion of participants who were unable to complete the HTKS-R assessment protocol may have introduced a degree of selection bias, potentially limiting the representativeness of the final sample. A second limitation is related to the relatively small number of clusters used for randomisation. Although the cluster-based design enhanced ecological validity, the relatively small number of clusters may have limited the precision of cluster-level estimates. In addition, school-specific contextual factors may not have been fully captured despite accounting for clustering statistically. Since the intervention only lasted 8 weeks, we cannot determine if the changes measured in behavioural self-regulation and reactive agility will be maintained beyond this period. Future studies involving larger numbers of schools and longer follow-up periods are warranted. Another limitation relates to the outcome measures used. While all selected outcome measures were appropriate and sensitive to change, anticipatory processing, perceptual–cognitive efficiency, and perception–action coupling were not directly measured, limiting direct interpretation of the mechanisms underlying the observed effects. Additional neurocognitive and observational assessments may help clarify the mechanisms through which the intervention produced its effects. An additional limitation is that outcome assessors could not be blinded to group allocation; therefore, measurement-related bias cannot be completely excluded. Although procedures were implemented to reduce practice effects associated with repeated HTKS-R administration, some residual influence of repeated testing may have remained. Finally, increased engagement or motivation associated with participation in a novel intervention may have contributed to part of the observed improvements.

Future Research

Further research needs to occur using other populations or environments to validate the current findings. Future studies should include longitudinal studies to look at the longevity of the training effects. Future interventions should look toward the addition of technology to help develop stronger anticipatory processing through perceptual-cognitive elements. Additionally, research that examines the relationship between transfer of training effects to academic performance or functional outcomes in the real world would be beneficial to determining how broadly applicable training driven by anticipation is within education.

Conclusion

The present study suggests that anticipation-driven locomotor training may be a promising approach for enhancing both behavioural self-regulation and reactive agility in children. By systematically incorporating cognitive demands into structured, progressively constrained movement tasks, the intervention was designed to integrate executive-function-related demands and perceptual–motor challenges into a unified movement framework. The magnitude and consistency of the observed effects highlight the importance of explicitly incorporating anticipatory and decision-making elements within physical education contexts. Although the mechanisms underlying these effects were not directly assessed, the findings support the potential value of incorporating anticipation-oriented task demands within structured movement activities. These findings provide additional support for integrating cognitively enriched and anticipation-oriented training approaches alongside traditional motor-focused practices in child development settings. From a theoretical perspective, the findings contribute to the growing body of literature linking cognitive and motor development within ecologically valid movement contexts. These findings have important practical implications for the design of school-based physical education programs, highlighting the value of integrating anticipatory and cognitively demanding tasks to enhance both cognitive and motor development in children.

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