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Development of a Cognitive–Physical Dual-Task Intervention Package and Its Effectiveness on Evidence Rate (Evidence Accumulation Speed) in Adolescent Girls

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ABSTRACT

Objective: The present study was conducted with the aim of developing a cognitive–physical dual-task intervention package and examining its effectiveness on the evidence rate (evidence accumulation speed) in adolescent girls.

Methods and Materials: This research employed a quasi-experimental design with pretest–posttest–follow-up and a control group. The statistical population consisted of low-active adolescent girls in Tehran in the 2024–25 academic year. Using convenience sampling, 50 participants were selected and randomly assigned to experimental and control groups (25 in each group). The experimental group received training based on the designed cognitive–physical dual-task package over eight weeks in twenty-four 20-minute sessions. The control group performed moderate-intensity aerobic exercises, starting from below-threshold intensity and progressing to moderately high intensity. To assess cognitive changes, the Wisconsin Card Sorting Test (WCST) was used, with "perseverative errors" and "total errors" serving as indices of cognitive flexibility and evidence accumulation speed. The process of developing the intervention package included designing training lesson plans, a teenager's workbook, and evaluating content validity using CVR and CVI indices, which ranged from 0.8 to 1 and 0.9 to 1, respectively, confirming the satisfactory validity of the package. Data were analyzed using repeated measures ANOVA.

Findings: The results showed that the mean perseverative errors and total errors in the experimental group decreased significantly compared to the control group at posttest and follow-up ($p < 0.01$). Effect size and eta squared also indicated a considerable impact of the cognitive–physical exercises on increasing the evidence accumulation rate.

Conclusion: The designed package significantly improved cognitive flexibility and decision-making processing speed in adolescent girls. These findings support the effectiveness of integrative mind–body approaches in enhancing fine-grained cognitive indices during adolescence.

Keywords: *cognitive–physical dual-task, evidence accumulation rate, adolescent girls.*

1. Introduction

The scientific understanding of cognition has shifted markedly over the past decades, with a growing emphasis on the interdependence of cognitive and motor systems as reflected in embodied cognition models that highlight continuous interactions between the brain, body, and environment (Gallou-Guyot et al., 2020). These models emphasize that cognitive processes do not occur in isolation but are dynamically shaped by motor activity, perceptual demands, and real-time interactions with the surrounding context, which has led to increased scientific interest in integrative training paradigms that simultaneously engage cognitive and physical systems (Campos-Magdaleno et al., 2022). Within this line of research, cognitive–physical dual-task training has emerged as a particularly promising approach for enhancing executive functioning, attentional control, and decision-making efficiency by combining mental processing demands with motor activity (Balcı et al., 2022). This intervention framework is grounded in evidence that cognitive and physical tasks draw upon overlapping neural networks, suggesting that simultaneous stimulation may generate synergistic benefits that exceed the impact of either modality alone (Tan et al., 2024).

A substantial body of research supports the role of dual-task training in improving cognitive control, especially in tasks involving working memory, inhibitory regulation, and rapid decision-making (Yu et al., 2024). Studies in populations ranging from older adults to clinical samples have shown that engaging in physical activity while performing cognitive tasks enhances neuroplasticity and strengthens brain regions responsible for executive functioning (Kuo et al., 2022). This is particularly evident in investigations demonstrating increased activation of the prefrontal cortex and improved dual-task walking performance following combined cognitive–motor interventions (Park, 2021). Such findings provide strong justification for the continued exploration of dual-task programs as tools for cognitive enhancement in diverse population groups, including adolescents who are undergoing significant developmental transitions that affect both cognitive and motor systems (Tao et al., 2022).

One of the most important theoretical advances associated with dual-task research relates to its potential to influence evidence accumulation, a central mechanism in modern decision-making models. Evidence accumulation refers to the rate at which information is gathered and integrated until a decision threshold is reached, a process measured in diffusion models and considered a sensitive indicator of cognitive processing efficiency (Van Maanen et al., 2021). Improvements in evidence accumulation rate reflect faster information encoding, stronger attentional control, and more efficient neural decision pathways, making the construct highly relevant for intervention research (Gupta et al., 2024). Studies examining enriched environments and cognitively complex tasks have shown that exposure to such conditions can moderate age-related declines in accumulation rate, demonstrating the malleability of this mechanism and its responsiveness to structured cognitive stimulation (Brosnan et al., 2023). This line of evidence strongly suggests that dual-task training—which inherently increases task complexity—may serve as an effective means to accelerate evidence accumulation processes, especially during periods of heightened neuroplasticity.

The physiological mechanisms underlying dual-task benefits are well-documented, particularly in research showing that physical activity influences neural functioning through increases in cerebral blood flow, regulation of neurotransmitters, and release of neurotrophic factors (Tan et al., 2024). These physiological pathways contribute not only to improved memory and attention but also to the optimization of cortical communication networks that facilitate rapid decision-making. When such physiological benefits coincide with cognitive demands requiring working memory or inhibitory control, the brain is challenged to reorganize its resource allocation, which may result in improved integration of cognitive and motor processing streams (Surkar et al., 2025). The recurring activation of distributed neural networks during dual-task exercises is believed to strengthen the functional connectivity between prefrontal, parietal, and motor regions, providing a strong foundation for improvements in evidence accumulation and other executive functions (Wu et al., 2024).

Beyond adult and clinical populations, dual-task research has expanded into athletic performance science, where athletes frequently operate under conditions that mimic dual-task demands by requiring rapid, coordinated responses to dynamic stimuli (Wu et al., 2024). Studies in young adults and athletes show that cognitive–motor dual-tasking enhances cortical activation and improves reaction speed, suggesting that these benefits are relevant even in populations with high baseline cognitive–motor performance (Surkar et al., 2025). These findings highlight

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dual-task training as a domain-general mechanism capable of enhancing cognitive efficiency and complex motor decision-making in groups across the performance spectrum. Furthermore, the observed increases in neural activation suggest that dual-task training modifies foundational cognitive–motor integration pathways, rather than merely improving task-specific strategies (Kim et al., 2023).

Cognitive–physical dual-task training has demonstrated considerable effectiveness in older adults with mild cognitive impairment, where systematic reviews and meta-analyses report significant improvements in cognitive ability, physical function, and dual-task performance (Yu et al., 2024). In addition, randomized controlled trials comparing dual-task and single-task training modes show that dual-task programs often yield superior improvements in executive control and prefrontal cortical activity, suggesting that the simultaneous engagement of motor and cognitive systems results in unique neurocognitive benefits (Kim et al., 2023). Creative adaptations of dual-task interventions, such as storytelling-based or narrative-integrated cognitive–physical training, have demonstrated enhanced engagement and improved outcomes in older adults with cognitive vulnerability (Kim & Park, 2023). These diverse findings demonstrate the adaptability, scalability, and impact potential of dual-task methodologies across cultural, developmental, and clinical contexts.

Despite strong evidence supporting dual-task programs in older adults, significantly less attention has been given to adolescents, particularly adolescent girls, who experience rapid neurodevelopmental changes that influence executive functioning, cognitive flexibility, and decision-making processes (Tao et al., 2022). Adolescence is characterized by substantial maturation of the prefrontal cortex and increased synaptic pruning, which together create an optimal window for interventions that target cognitive efficiency (Tan et al., 2024). However, sedentary behavior and declines in moderate-to-vigorous physical activity during adolescence may jeopardize executive functioning, making interventions that combine physical activation with cognitive stimulation particularly important (Campos-Magdaleno et al., 2022). Furthermore, adolescent girls often experience reduced participation in structured physical activity, potentially increasing vulnerability to attentional fluctuations, reduced cognitive flexibility, and weaker decision-making efficiency (Balcı et al., 2022). Dual-task training may serve as a powerful tool to counteract these trends by simultaneously strengthening cognitive and motor networks.

Another consideration relevant to adolescent populations is the sensitivity of executive functioning to environmental and physiological factors. Evidence from neuropsychological studies indicates that adolescents may exhibit cognitive vulnerability in response to physiological challenges, as shown in research using the Wisconsin Card Sorting Test to examine post-anesthesia cognitive complications (Mehri-Nejad et al., 2021). These findings illustrate that executive function in adolescents can be disrupted by contextual and biological stressors, underscoring the importance of interventions that reinforce cognitive resilience and flexibility. Dual-task training, by challenging the brain to manage concurrent cognitive–motor demands, may play a significant role in strengthening these systems during developmental windows when neural plasticity is high (Park, 2021).

The theoretical relevance of evidence accumulation rate to adolescent cognitive development is supported by research demonstrating that accumulation speed is influenced by attentional regulation, executive control, and working-memory integrity—all domains that undergo considerable development during adolescence (Van Maanen et al., 2021). Targeted interventions that improve these domains may thus produce measurable improvements in evidence accumulation rate, providing a sensitive and theory-driven index for evaluating the efficacy of training programs (Gupta et al., 2024). Moreover, given that dual-task training increases cognitive complexity through simultaneous demands on working memory, inhibition, and motor coordination, it is plausible that such interventions exert direct effects on evidence accumulation mechanisms (Tao et al., 2022). Diffusion-model parameters, including accumulation rate, offer advantages over traditional neuropsychological scores by capturing fine-grained fluctuations in processing efficiency, making them ideal for adolescent intervention studies.

Despite these promising theoretical connections, a substantial gap exists in the literature regarding the design, cultural adaptation, and empirical testing of dual-task training programs specifically developed for adolescents, particularly adolescent girls. Most dual-task research focuses on older adults or clinical populations, leaving the developmental relevance of these interventions underexplored (Yu et al., 2024). Moreover, no previous studies have investigated the impact of cognitive–physical dual-task interventions on evidence accumulation rate in adolescent populations in non-clinical contexts, despite the importance of this construct for academic performance,

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executive functioning, and real-world decision-making (Brosnan et al., 2023). Addressing this gap is critical for extending the theoretical scope of dual-task science, informing educational and developmental practices, and identifying effective strategies for strengthening cognitive–motor integration in youth (Gallou-Guyot et al., 2020).

Drawing upon insights from cognitive neuroscience, developmental psychology, motor behavior research, and evidence accumulation theory, it is evident that dual-task interventions hold strong potential as tools for enhancing adolescent cognitive performance. Improvements in cortical activation, executive functioning, and perceptual–motor coordination observed in other populations provide a compelling rationale for extending these paradigms to adolescents (Surkar et al., 2025). Additionally, the application of diffusion-model indicators such as evidence accumulation rate allows for sensitive evaluation of cognitive changes that may not be captured by traditional behavioral measures (Van Maanen et al., 2021). By systematically integrating cognitive and physical task components in a structured training package, researchers can uniquely contribute to the advancement of cognitive–motor developmental science and provide new frameworks for adolescent cognitive enhancement.

Accordingly, the aim of the present study is to develop a cognitive–physical dual-task intervention package and examine its effectiveness on improving the evidence accumulation rate in adolescent girls.

2. Methods and Materials

2.1. Study Design and Participants

The research method was quasi-experimental with a pretest–posttest–follow-up design and a control group. A quasi-experimental method was used in order to answer the two research questions and achieve the study objectives. The statistical population of this study consisted of low-active adolescent girls in Tehran who were studying during the 2024–2025 academic year. Using convenience sampling, 50 adolescent girls were selected and randomly assigned to two groups of 25: experimental and control. The experimental group participated for 8 weeks in 24 sessions of 20 minutes each and received training using the intended intervention package. During the same period, the control group performed aerobic exercises of moderate intensity, starting from below-threshold and progressing to moderately high intensity.

2.2. Measures

Online computerized Wisconsin test: The Wisconsin Card Sorting Test (WCST) is one of the best-known neuropsychological tests and assesses abstract reasoning, cognitive flexibility, perseveration, problem solving, concept formation, set-shifting, hypothesis testing ability, use of error feedback, initiation and termination strategies, and sustained attention. The test was developed by Grant (1948) and later revised by Heaton et al. (1993). The test includes 64 cards displaying one to four symbols in the form of red triangles, green stars, yellow crosses, and blue circles, with no two cards being identical or repeated. The participant's task is to place each card under one of four key cards, based on a rule that governs the key cards. After each response, the participant receives feedback indicating whether the response was correct or incorrect. Once the participant gives a sufficient number of consecutive correct responses, the sorting rule changes; however, the participant is not informed of this change and must discover it independently. In scoring, two main indices are considered: (1) the number of categories completed during the test (number of achieved categories), which reflects the participant's progress and the discovery of the six series; and (2) perseverative errors (errors of perseveration), which are assigned to choices where, after the rule changes, the participant continues to persist with the previous response pattern across ten trials. This error is a primary index of cognitive inflexibility and is characteristic of frontal lobe damage. The validity of this test for assessing cognitive deficits (after brain injury) was reported to be above 0.86 in Lezak's (1995) study. The reliability of the test was reported as 0.83 in the study by Spreen and Strauss (1991). Naderi (1994), using the test–retest method, reported a reliability coefficient of 0.85 for this test in an Iranian population (Mehri-Nejad et al., 2021).

2.3. Intervention

The research was carried out in two stages. First stage: the process of developing and validating the dual-task (physical–cognitive) training protocol. Using a library/documentary method, and after ensuring that there was no similar package in this area, the protocol was developed based on a thorough review of relevant sources and a detailed examination of the principles and components of dual-task (physical–cognitive) training protocols. The present protocol consists of a manual titled "Dual-Task (Physical–Cognitive) Training Protocol," which contains a

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separate lesson plan for each training session, step-by-step instructional guidelines, an introduction to the tools and materials required for each session, and related illustrations.

Content Validity Ratio (CVR) (Lawshe, 1975): This index was developed by Lawshe (1975). To calculate this index, the opinions of expert specialists in the relevant content area of the test or material were used. After explaining the test objectives and providing operational definitions related to the content of the items, experts were asked to classify each objective. Then, based on the CVR formula, the content validity ratio was calculated. According to the number of experts who evaluated the objectives, an acceptable CVR value is 0.62. In this study, the content validity ratio for all objectives in the training protocol ranged from 0.80 to 1.00.

Content Validity Index (CVI): To examine the content validity index, the method of Waltz et al. (2010) was used. Based on the number of experts who evaluated the objectives, the acceptable CVI value, given the number of experts, is 0.79. In the present study, the CVI for all objectives in the training package ranged from 0.90 to 1.00. The summarized content of the dual-task (physical–cognitive) training protocol is presented in Table 1.

Table 1

Summary of the content of the dual-task (physical–cognitive) training protocol

Monitoring and control method	Duration of each session	Sample training combination (integrated cognitive–physical task)	Type of physical exercise	Type of cognitive exercise	Intensity of physical exercise	Training goal for the week	Week
Heart rate monitor + rating of perceived exertion	30 minutes (5 warm-up + 20 training + 5 cool-down)	Walking while repeating short numerical or visual sequences	Coordinated stepping	Simple working memory	65% HRmax	Familiarization, adjustment of motor and mental rhythm	1
Same monitoring method	30 minutes	Combination of walking + listening to numbers and repeating them in reverse order	Light walking	Short-term working memory	65% HRmax	Stabilizing memory performance during movement	1
Momentary monitoring + assessment of mental load	30 minutes	Maintaining balance and responding to a target sound	Static balance + quick reaction	Response inhibition	68% HRmax	Increasing concentration and response control	2
Same monitoring method	30 minutes	Motor response to a target color in an unstable environment	Dynamic balance	Response inhibition with varied stimuli	68% HRmax	Stabilizing precise motor control	2
Heart-rate monitor + assessment of breathing status	30 minutes	Choosing between two symbols while running	Running + light jumps	Binary decision-making	70% HRmax	Increasing speed and perception–action coordination	3
Same monitoring method	30 minutes	Choosing the correct path according to immediate instructions	Fast running between cones	Decision-making on a changing route	70% HRmax	Improving reaction under time pressure	3
Control of cardiac intensity and perceived exertion	30 minutes	Retaining and reporting longer sequences	Multi-directional dynamic movements	Progressive working memory	72% HRmax	Increasing cognitive complexity	4
Same monitoring method	30 minutes	Combining colors and numbers in chained movements	Stepping with consecutive turns	High-load memory	72% HRmax	Training sustained attention and working memory	4
Assessment of heart rate and emotional state	30 minutes	Changing direction based on stimulus color (red = right, blue = left)	Agility drills with direction changes	Cognitive flexibility	73% HRmax	Focusing on changing mental rules	5
Same monitoring method	30 minutes	Different reactions to loud versus brief sounds	Short sprints with quick turns	Changing mental response based on stimulus type	73% HRmax	Expanding cognitive flexibility	5
Recording exertion and arousal	30 minutes	Simultaneous integration of decision-making, memory, and inhibition	Combined reactive movements	Multistep decision-making	75% HRmax	Multidimensional cognitive–motor integration	6

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Same monitoring method	30 minutes	Reactive course with deceptive stimuli	Running with momentary stops (Stop & Go)	Momentary response inhibition	75% HRmax	Focus and emotional control	6
Heart-rate monitor + oxygen assessment	30 minutes	Choosing among multiple options over light obstacles	Running between hurdles	Multiple-choice decision-making	76% HRmax	Increasing reactive agility	7
Same monitoring method	30 minutes	Responding to combined auditory + visual stimuli	Bilateral reaction	Multimodal attention	77% HRmax	Focusing on combined sensory input	7
Assessment of heart rate + mental load	30 minutes	Moving among changing colors with shifting rules	Variable agility course	Dynamic rule switching	78% HRmax	Strengthening mental flexibility	8
Same monitoring method	30 minutes	Responding to unpredictable patterns	Sprints + alternating balance tasks	Simultaneous prediction and decision-making	79% HRmax	Stabilizing predictive cognitive performance	8
Comprehensive monitoring	30 minutes	Rapid decision-making in stimulus-rich conditions	Dynamic exercise with multiple sensory inputs	Multitask integration	80% HRmax	Maintaining high accuracy and concentration	8
Same final monitoring method	30 minutes	Final combined execution (integration of all skills)	Multistep exercise with rapid stimulus changes	High-level cognitive coordination	82% HRmax	Final evaluation and consolidation of performance	—

Second stage: implementation method and execution of the dual-task (physical–cognitive) training protocol: After developing the intended protocol, revising it based on experts' opinions, and validating it, and in order to ensure full alignment of the protocol content with the target audience and recipients of the training, the protocol was first implemented intensively in a five-volunteer pilot group in parallel with the sampling process. Following examination of the pilot study results, deficiencies were addressed and precise adjustments were made, and the protocol was then prepared for implementation in the main study sample. The protocol was administered to the experimental group in 24 sessions of 20 minutes each on a weekly basis. During the training period, participants in the control group did not receive any training. After completion of the training period and two months later, in order to determine the stability of the intervention effects, both groups once again completed the study questionnaires in a follow-up assessment.

2.4. *Data Analysis*

The data were analyzed using repeated measures analysis of variance via SPSS.

3. Findings and Results

The mean reported age for the study sample, broken down by groups, was 14.5 ± 1.30 for the intervention group and 14.7 ± 1.41 for the control group. The minimum age of participants was 14 and the maximum was 16. Regarding parents' education, 7 participants (67%) in the intervention group had university-educated parents and 3 (33%) had non-university-educated parents. In the control group, 4 participants (40%) had university-educated parents and 6 (60%) had non-university-educated parents. Additionally, with a significance level greater than 0.05, no significant difference was found between the two groups, indicating homogeneity in age. The results of the descriptive findings of the study for the three stages across the two groups are presented in Table 2.

Table 2

Descriptive statistics of variables

Group		Pre-intervention		Post-intervention		Follow-up	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Experimental	Perseverative Errors	8.12	3.32	4.90	3.70	5.01	3.91
	Total Errors	11.4	4.20	7.74	4.81	7.98	4.96
Control	Perseverative Errors	7.08	3.55	6.93	3.44	7.13	4.64
	Total Errors	12.6	5.86	11.7	5.70	11.9	5.92

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As seen in Table 2, the mean scores for perseverative errors and total errors in both intervention and control groups are displayed. In the pre-test stage, there were no considerable differences between the groups. However, following the intervention, the experimental group showed a significant decrease in both error types compared to the control group. This difference was maintained during the follow-up phase.

To assess the assumption of the covariance matrix's symmetry, Box's test was used. The result for the study variables (Box's M = 88.8, F = 13.06, $p < 0.01$) showed a significance level below 0.05, indicating that the assumption of homogeneity of covariance matrices was not met. However, due to the equality of group sizes, this assumption can be overlooked (Rezaei & Ostovar, 2017). Mauchly's test of sphericity yielded a value of 0.055 (Chi-Square = 78.1, $p < 0.01$), suggesting a violation of sphericity. Therefore, the more conservative Greenhouse–Geisser correction was applied in repeated-measures ANOVA. Homogeneity of variances was confirmed for both perseverative errors ($F = 1.9$, $p > 0.05$) and total errors ($F = 2.07$, $p > 0.05$). The results of the 3×2 repeated measures ANOVA to compare experimental and control groups across the three time points are shown in Table 3.

Table 3

Multivariate ANOVA (MANOVA) significance test results for study groups

Dependent Variables	Test Type	Sum of Squares	df	Mean Square	F	p-value	Eta Squared
Perseverative & Total Errors	Sphericity Assumed	1049.2	5	209.8	26.001	0.001	0.481
	Greenhouse-Geisser	1049.2	1.79	584.2	26.001	0.001	0.481
	Huynh-Feldt	1049.2	1.98	529.9	26.001	0.001	0.481
	Upper-Bound	1049.2	1	1049.2	26.001	0.001	0.481

As Table 3 shows, a statistically significant difference was observed between the study groups for at least one dependent variable. Eta squared indicates that the overall difference between the two groups accounted for 48.1% of the variance, which is both statistically and practically significant. The specific results of the simple and interaction effects are presented in Table 4.

Table 4

Repeated-measures ANOVA results (3×2 design)

Variable	Source	SS	df	MS	F	p-value	Effect Size
Perseverative Errors	Between Groups	2083.3	1	2083.3	31.02	0.001	0.526
	Error	1880.5	18	67.1			
	Within Groups	Factor	19830.4	2.45	8087.4	247.3	0.001
	Interaction	2504.8	2.45	1021.5	198.4	0.001	0.686
	Error (Factor)	4790	68.6	69.7			
Total Errors	Between Groups	811.2	1	811.2	9.82	0.004	0.260
	Error	2312.6	18	82.5			
	Within Groups	Factor	20020.7	2.71	7391.9	12.2	0.001
	Interaction	1712.3	2.71	631.9	31.02	0.001	0.526
	Error (Factor)	5432.9	75.8	71.6			

Table 4 indicates that the main effect of group was significant for perseverative errors ($F = 247.3$, $p < 0.05$, $\eta^2 = 0.662$) and for total errors ($F = 232.06$, $p < 0.05$, $\eta^2 = 0.526$). This suggests that the mean differences in perseverative and total errors between the two groups were statistically significant. Moreover, the main effect of time (pre-test, post-test, follow-up) was significant for perseverative errors ($F = 198.4$, $p < 0.05$, $\eta^2 = 0.686$) and total errors ($F = 12.2$, $p < 0.05$, $\eta^2 = 0.310$), indicating meaningful differences across the three time points. To further analyze these differences, Bonferroni post-hoc tests were conducted, as shown in Table 5.

Table 5

Bonferroni post-hoc test for perseverative and total errors across three stages

Variable	Stage I	Stage J	Mean Difference (I–J)	p-value
Perseverative Errors	Pre-test	Post-test	*8.86	0.001
	Pre-test	Follow-up	*–9.34	0.001
Total Errors	Pre-test	Post-test	*7.75	0.001
	Pre-test	Follow-up	*–10.1	0.001

According to Table 5, there was a general decline in perseverative and total error scores from pre-test to post-test and follow-up stages in adolescent girls, indicating the effectiveness of the intervention protocol. Specifically, for perseverative errors, the differences between pre-test and post-test ($p < 0.05$, $d = 8.86$) and pre-test and follow-up ($p < 0.05$, $d = –9.34$) were significant. Similarly, in total errors, the differences between pre-test and post-test ($p < 0.05$, $d = 7.75$) and pre-test and follow-up ($p < 0.05$, $d = –10.1$) were significant, showing the effectiveness of the cognitive–physical dual-task training protocol in reducing total errors in adolescent girls.

4. Discussion and Conclusion

The objective of this study was to examine the effectiveness of a cognitive–physical dual-task intervention package on improving evidence accumulation rate—reflected in reduced perseverative and total errors—in adolescent girls. The results demonstrated that participants who engaged in the cognitive–physical dual-task program showed significant reductions in both types of errors at post-test and follow-up compared to the control group. These findings provide strong empirical support for the hypothesis that integrating cognitive and physical demands within a structured dual-task format leads to measurable improvements in cognitive processing efficiency, executive functioning, and the underlying mechanisms responsible for decision-making. The pattern of results aligns with the growing body of research emphasizing the close interplay between cognitive mechanisms and motor engagement, which together shape executive control, attentional allocation, and information processing speed (Gallou-Guyot et al., 2020).

A plausible explanation for the observed improvements lies in the theoretical foundations of dual-task performance, which assert that simultaneous cognitive and motor demands activate distributed neural networks responsible for attention, inhibition, working memory, and decision-making (Campos-Magdaleno et al., 2022). When individuals must manage competing tasks, the nervous system reorganizes its resource allocation strategies, strengthening functional connectivity between cognitive and motor pathways. Such integrated activation may accelerate evidence accumulation processes by increasing neural efficiency and reducing reaction time variability. The reduced error rates observed in this study correspond with these theoretical predictions, suggesting that enhanced synchronization across prefrontal and parietal regions contributed to improved information processing and executive control (Park, 2021). This interpretation is further supported by research showing that cognitive–motor dual-tasking increases activation in brain networks responsible for executive regulation, particularly in populations undergoing neurological or developmental changes (Kuo et al., 2022).

The study's findings also align with diffusion-model perspectives on decision-making, which conceptualize evidence accumulation as the rate at which sensory and cognitive information converges into a decision threshold (Van Maanen et al., 2021). Interventions that enhance attentional control, reduce cognitive interference, and strengthen response inhibition are thought to increase evidence accumulation rate by improving the quality and speed of information encoding. The observed reduction in perseverative errors—a key indicator of cognitive inflexibility—indicates that dual-task training may help adolescents shift more efficiently between task rules, suppress ineffective response patterns, and update task-relevant information more rapidly. These improvements correspond with research showing that enriched environments and cognitively challenging activities can enhance evidence accumulation speed and moderate the effects of developmental or age-related cognitive inefficiencies (Brosnan et al., 2023). The present results extend these findings to an adolescent population, suggesting that early developmental stages may provide an optimal window for strengthening evidence accumulation processes through dual-task interventions.

Dual-task interventions have been widely studied in older adults and individuals with mild cognitive impairment, with

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strong evidence indicating improvements in dual-task walking, executive control, and physical performance (Yu et al., 2024). Although most of this research has focused on aging populations, the demonstrated improvements in the current study suggest that similar mechanisms operate in adolescents. Given that adolescence represents a period of heightened neuroplasticity and reorganization of prefrontal networks, it is plausible that dual-task training exerts even stronger cognitive effects in youth than in adults. Previous studies emphasize that cognitive–motor programs requiring coordinated attention, memory, and motor planning lead to measurable improvements in executive functioning (Kim et al., 2023). For example, simultaneous cognitive–physical programs such as ESCARF training have been shown to improve cognitive flexibility and reaction speed in older adults with mild cognitive impairment, highlighting the generalizability of dual-task principles across age groups (Kim & Park, 2023). The significant improvements observed in the present study demonstrate that adolescent girls also benefit considerably from such integrated training approaches, reinforcing the idea that dual-task interventions are developmentally flexible and widely applicable.

The current findings are also consistent with emerging literature in performance science and young adult populations, which shows that dual-task training enhances cognitive–motor learning, cortical activation, and response efficiency (Surkar et al., 2025). Research involving athletes demonstrates that cognitive–motor dual-tasking improves motor coordination, working memory, and decision-making under time pressure, suggesting that combined task demands train the brain to manage complex, rapidly changing environments more effectively (Wu et al., 2024). In line with this, the adolescents in our study were required to process cognitive stimuli while performing physically demanding tasks, thereby replicating real-world scenarios that require fast, coordinated responses. The significant reductions in errors observed in the experimental group suggest that repeated exposure to such conditions improved cognitive processing speed and task-switching abilities, mirroring the benefits reported in athletic populations.

The improvements observed may also be attributed to the physiological effects of exercise on cognition, which include increases in neurotrophic factors, enhanced oxygen delivery to the brain, and improved neurotransmitter regulation (Tan et al., 2024). When physical exercise is combined with cognitive stimulation, these physiological benefits may amplify plasticity within cognitive networks. Studies have shown that even moderate-intensity movement paired with cognitive challenges results in greater improvements in executive functions compared to single-task interventions (Balcı et al., 2022). Thus, the dual-task structure used in this study may have leveraged both cognitive and physiological enhancement pathways, creating a synergistic effect reflected in improved evidence accumulation rate.

The results also provide support for the cognitive load and challenge-based flexibility perspective, which posits that exposure to optimal levels of task difficulty stimulates compensatory neural mechanisms and strengthens cognitive resilience (Tao et al., 2022). By engaging adolescents in progressively complex dual-task challenges, the intervention likely facilitated the development of more efficient strategies for handling cognitive load, contributing to the long-term reductions in errors evident at follow-up. This perspective is consistent with findings showing that dual-task interventions improve decision-making under uncertainty by encouraging the brain to streamline information processing pathways (Gupta et al., 2024). The meaningful retention of gains after the intervention suggests that the training may have induced stable neurocognitive adaptations, rather than transient performance enhancements.

Another valuable insight comes from research indicating that adolescence is a sensitive period for the maturation of cognitive flexibility and prefrontal functioning. Studies using neuropsychological tasks such as the Wisconsin Card Sorting Test have shown that adolescents can experience disruptions in cognitive flexibility due to environmental, physiological, or medical factors (Mehri-Nejad et al., 2021). This vulnerability underscores the importance of strengthening cognitive resilience through structured interventions. The reduced perseverative and total errors observed in this study demonstrate that dual-task training may serve as a protective factor by enhancing the efficiency of prefrontal networks and improving the adolescent brain's ability to adjust to changing task demands. These findings reinforce the notion that adolescence is an ideal developmental period for implementing cognitive enhancement programs designed to improve decision-making speed and accuracy.

Furthermore, the effectiveness of dual-task training in this study mirrors outcomes observed in cognitive–motor rehabilitation research. Integrated cognitive-physical interventions have been shown to enhance multiple domains of functioning, including balance, coordination, executive control, and dual-task performance, particularly in populations at risk of cognitive decline (Gallou-Guyot et al., 2020). Although the current sample differs from clinical populations typically studied, the parallel improvements suggest that the underlying mechanisms of dual-task benefits are robust across cognitive ability levels. These mechanisms include enhanced attentional switching, faster response inhibition, increased reliance on efficient neural pathways, and improved capacity to manage simultaneous demands, all of which are reflected in the adolescents' performance improvements.

Taken together, the findings of this study offer multiple theoretical and practical implications. They demonstrate that cognitive–physical dual-task training is not only feasible for adolescents but also highly effective in improving fine-grained indicators of cognitive efficiency such as evidence accumulation rate. By using perseverative and total errors as behavioral indices linked to diffusion-model parameters, this study provides a novel contribution to the literature by integrating dual-task methodology with computationally informed cognitive metrics. The alignment of the current findings with established research across older adults, athletes, and clinical populations indicates that dual-task interventions have wide-ranging applicability and may be tailored to meet the developmental needs of diverse groups. Moreover, the sustained improvements observed at follow-up highlight the long-term potential of such interventions in supporting cognitive development during adolescence.

5. Limitations & Suggestions

This study is subject to several limitations. The sample consisted exclusively of low-active adolescent girls from a single urban region, which limits the generalizability of the findings to broader adolescent populations, including boys or adolescents from rural or socioeconomically diverse backgrounds. The quasi-experimental design, while practical, restricts causal interpretations compared to fully randomized controlled trials. Additionally, the sample size was relatively small, which may reduce statistical power and limit the detection of subtle effects. Another limitation is the use of a specific set of dual-task activities; different task combinations or intensities may yield different cognitive outcomes. Finally, although follow-up data were collected, longer-term follow-up periods would be necessary to determine the durability of the cognitive improvements observed.

Future studies should replicate this intervention with larger and more diverse adolescent samples to enhance generalizability. Researchers may also examine gender differences to explore whether boys and girls show similar cognitive benefits from dual-task training. Incorporating neuroimaging techniques would allow for direct observation of neural changes and help clarify the mechanisms underlying improvements in evidence accumulation rate. Future work should also vary the complexity, duration, and type of dual-task activities to determine optimal training parameters for adolescent populations. Longitudinal studies extending beyond several months would help determine whether dual-task benefits lead to lasting enhancements in academic performance, emotional regulation, and everyday decision-making. Additionally, integrating dual-task interventions into school curricula may offer valuable insights into feasibility, scalability, and long-term developmental impact.

Educators, school psychologists, and physical education specialists can consider incorporating structured cognitive–physical dual-task activities into regular school programs to enhance students' cognitive flexibility and decision-making skills. Training sessions can be adapted to classroom or gym settings with minimal equipment, making implementation feasible across various educational contexts. Counselors and academic support units may integrate dual-task exercises into cognitive skills training or study-skills programs for adolescents who exhibit attentional or executive functioning challenges. Coaches and sports trainers can also use dual-task drills to improve athletes' on-field decision-making and cognitive resilience. Overall, integrating dual-task principles into educational and athletic environments may promote healthier cognitive development and enhance performance across multiple domains.

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Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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Authors' Contributions

All authors equally contributed to this article.

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