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Research Article

Combined Effects of Perceptual–Motor Interventions and Transcranial Direct Current Stimulation on Motor Competence in Children with Developmental Coordination Disorder

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Background

Developmental coordination disorder (DCD) is a common neurodevelopmental condition in children, characterized by deficits in both actual motor competence (AMC) and perceived motor competence (PMC).

Objective

This study aimed to investigate the effects of linear and non-linear perceptual–motor intervention, with or without transcranial direct current stimulation (tDCS), on AMC and PMC in children aged 7–9 years with DCD.

Methods

A quasi-experimental pre-test–post-test design with four groups was used: (i) Linear pedagogy (LP) perceptual–motor intervention, (ii) non-linear pedagogy (NLP) perceptual–motor intervention, (iii) tDCS combined with perceptual–motor intervention using the LP, and (iv) tDCS combined with perceptual–motor intervention using the NLP. A total of 40 children diagnosed with DCD based on the Movement Assessment Battery for Children-2 were randomly assigned to the groups. Perceptual–motor interventions were delivered over 10 sessions, and tDCS was applied to the right primary motor cortex for 20 min before each training session.

Results

Results showed that the group receiving NLP combined with tDCS exhibited the greatest improvements in both AMC and PMC compared to all other groups ($p<0.001$), whereas NLP alone also outperformed LP ($p<0.001$).

Conclusion

These findings suggest that combining brain stimulation with NLP can significantly enhance both AMC and PMC in children with DCD. Overall, the study highlights the importance of designing enriched, exploratory, and neuro-enhanced learning environments for the rehabilitation of children with motor coordination difficulties.

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1. INTRODUCTION

Developmental coordination disorder (DCD) is one of the relatively common neurodevelopmental disorders among school-aged children, characterized by difficulties in acquiring and performing motor skills. [1]Although its prevalence is estimated at approximately 5–6%, it is often underdiagnosed and can have widespread negative consequences on daily life and participation in physical activities.[2] Children with DCD typically demonstrate deficits in both actual motor competence (AMC; the objective ability to perform fundamental movements) and perceived motor competence (PMC; the subjective perception of their own abilities).[3,4] These two interrelated dimensions play a crucial role in psychological, physical, and social development. Poor actual performance tends to foster negative self-perceptions, leading children to avoid motor activities, which ultimately results in further skill deterioration and psycho–physical issues.[5] Therefore, interventions that simultaneously improve both AMC and PMC are essential for supporting children with DCD and promoting their holistic development.[6]

One effective approach for enhancing AMC and PMC in children with DCD involves combining perceptual–motor interventions[7] with transcranial direct current stimulation (tDCS).[8] Perceptual–motor interventions, by focusing on the systematic interaction between sensory input and movement, improve internal modeling and motor organization, thereby strengthening motor skills.[9] In parallel, tDCS, a novel and non-invasive method, enhances neuronal excitability by delivering a mild electrical current to the primary motor cortex (M1), and can assist in improving motor performance, particularly in children who experience delays in motor learning.[8] In addition, tDCS applies a weak, constant electrical current through scalp electrodes; typically, anodal stimulation increases excitability, whereas cathodal stimulation decreases it.[10,11] When tDCS is applied across repeated sessions and paired with behavioral training, it can facilitate Hebbian-like plasticity and consolidation processes, resulting in effects that extend beyond the stimulation period.[11] The direction and durability of these effects depend on stimulation parameters (e.g., montage, intensity, and duration) and participant characteristics (e.g., age, baseline performance).[10] A review of previous studies indicates that perceptual–motor interventions have generally been reported as effective. For instance, a study by Walters[12] demonstrated that a 6-week perceptual–motor program improved motor skills in children with DCD, and De Milander[7] reported significant improvements in balance following a 10-week perceptual–motor intervention. Similarly, a systematic review by Saha *et al.*[13] confirmed the effectiveness of these interventions in improving motor modeling, rhythmic coordination, postural control, and sensory–motor perception. Moreover, a study by Tajari *et al.*[14] showed that 21 sessions of perceptual–motor training led to improvements in cognitive inhibitory control and motor performance. In the tDCS literature, Grohs *et al.*[15] found that applying tDCS over the M1, in conjunction with skill training, facilitated stable motor skill learning. In addition, Akremi *et al.*[16] reported that cerebellar anodal tDCS reduced errors in the execution of motor sequences. Overall, the evidence suggests that both approaches can complement each other and may be effective in improving motor performance in children with DCD.[6]

In addition to these findings, several recent studies have combined motor interventions with tDCS and reported promising outcomes. For example, Hashemi *et al.*[17] conducted a quasi-experimental study with 80 boys aged 6–10 years, randomly assigned to three intervention groups (tDCS, physical exercise, and combined) and one control group, and found that the combined intervention produced the greatest improvements in locomotor movement skills. Similarly, Malboobi *et al.*[18] employed a pre–post design with four groups of 10 children each and reported that integrating badminton training with tDCS resulted in the most significant gains in motor coordination compared to either intervention alone. In line with these findings, another experimental study on 20 children revealed that combining tDCS with selected exercises improved balance performance across multiple sensory conditions, highlighting the added value of integrative approaches.[19] These studies, despite differences in design, consistently demonstrate that combining motor-based training with brain stimulation can enhance locomotor skills, coordination, and balance beyond what is typically achieved by single interventions. However, no study has directly examined the combined use of perceptual–motor interventions and tDCS. Considering the established benefits of each method separately, investigating their integration could provide new insights into optimizing interventions for children with DCD.

Despite the overall effectiveness of perceptual–motor interventions in children with DCD, instructional methods play a critical role in their outcomes, as children with motor difficulties require learning environments tailored to their individual and developmental characteristics.[20] In this regard, two main approaches to motor instruction have been proposed: Linear and non-linear pedagogy (NLP). Linear pedagogy (LP) emphasizes repetitive practice, fixed modeling, and direct feedback from the coach, aiming to guide the child toward accurate imitation of a correct movement.[21] In contrast, NLP, grounded in the ecological dynamics theory, views learning as the result of interactions among individual, environmental, and task constraints, and fosters motor skills through varied practice, exploration, indirect feedback, and active engagement in a meaningful and dynamic context.[22] These features make NLP a more effective option for children with DCD, who often experience frustration and decreased motivation during monotonous practice, as it enhances creativity, flexibility, self-confidence, and adaptability to real-world conditions.[23] Recent studies have confirmed the superiority of non-linear methods over linear methods in healthy children and on a variety of variables.[24-27] One previous study also reported that NLP was more successful than LP in improving creativity, decision-making, and team participation in children with DCD and attention-deficit/hyperactivity disorder.[28] Importantly, the principles of NLP align with the broader construct of physical literacy, as both emphasize movement learning as a holistic process that integrates physical competence with motivation, confidence, knowledge, and understanding.[29,30] In practice, by encouraging exploration, adaptability, and self-regulation, NLP nurtures the same multidimensional capacities that physical literacy seeks to develop, thereby positioning it not only as a method of instruction but also as a foundation for cultivating lifelong engagement in physical activity.[29-31] Nevertheless, direct examination of the differences between these two approaches in enhancing AMC and PMC in children with DCD still requires further research.[3,6,32]

Based on the topics discussed, the aim of the present study is to examine the effects of perceptual–motor interventions delivered through LP and NLP, alongside the complementary intervention of tDCS, on AMC and PMC in 7–9-year-old children with DCD. Based on this objective and the presented background, it is hypothesized that the NLP, when combined with tDCS, will have a greater impact on AMC and PMC in children with DCD. This study holds significant importance and necessity from various perspectives. First, AMC and PMC are considered key factors in psychomotor development, participation in physical and social activities, and even the mental health of children with DCD.[3,33,34] Neglecting it may lead to motor isolation, decreased self-esteem, and a lower quality of life in the long term.[3,33] At the same time, a literature review indicates that, to date, few studies have specifically examined the impact of perceptual–motor interventions on both components of AMC and PMC in children with DCD. Furthermore, no comprehensive research has compared modern motor instruction methods (linear and non-linear) while considering the complementary role of tDCS in perceptual–motor interventions for this particular group of children. This is critical because understanding the effects of such combined interventions could lead to the development of efficient and individualized rehabilitation programs.

2. MATERIALS AND METHODS

2.1. ETHICAL APPROVAL

All procedures were conducted in accordance with relevant ethical guidelines and principles, and the study adhered to all institutional and national research ethics standards for human participants. Before the quantitative survey, parents of all participants were comprehensively informed about the study's objectives, purpose, and the individuals responsible for conducting the survey. They were also provided with detailed information on the secure and compliant handling of their data in accordance with data protection regulations. Participation was voluntary, with participants having the right to withdraw at any time without consequences. Participant privacy and confidentiality were respected, and measures were taken to maintain anonymity. Parents of all participants provided written informed consent before the intervention began. The proposed research design was reviewed and approved by the Human Research Ethics Committee of Middle East Technical University under protocol code 0082-ODTUİAEK-2025 before the study was initiated.

2.2. RESEARCH DESIGN

This study employed a quasi-experimental design with a pre-test–post-test structure. Participants were divided into four groups: (i) Perceptual–motor intervention using the LP (Group 1), (ii) perceptual–motor intervention using the NLP (Group 2), (iii) tDCS combined with perceptual–motor intervention using the LP (Group 3), and (iv) tDCS combined with perceptual–motor intervention using the NLP (Group 4). The overall research design is illustrated in Figure 1.

2.3. PARTICIPANTS

To determine the sample size, a power analysis was conducted using G*Power software (version 3.1.9.2, Heinrich Heine Universität Düsseldorf, Germany) for a 4 (group) × 2 (test) analysis of variance ($\alpha = 0.05$, $1-\beta = 0.95$, effect size = 0.40), indicating a need for 32 participants.[35] Accounting for a 20% dropout rate,[36] and to accommodate common dropout rates in behavior-related studies,[35] 40 children (7–9 years old) with DCD from schools in Izmir were randomly assigned to four groups (10/group). It should be noted that the initial number of participants was 69, of whom 29 did not meet the study's inclusion criteria and were excluded. Demographic information, including gender distribution, is presented in Table 1.

2.4. INCLUSION AND EXCLUSION CRITERIA

The inclusion criteria for the study were: (i) Age between 7 and 9 years, (ii) school attendance with a complete health record, (iii) scoring below the 15th percentile on the Movement Assessment Battery for Children (MABC)-2 test, (iv) no receipt of psychomotor or occupational therapy interventions within the past 3 months, and (v) written informed

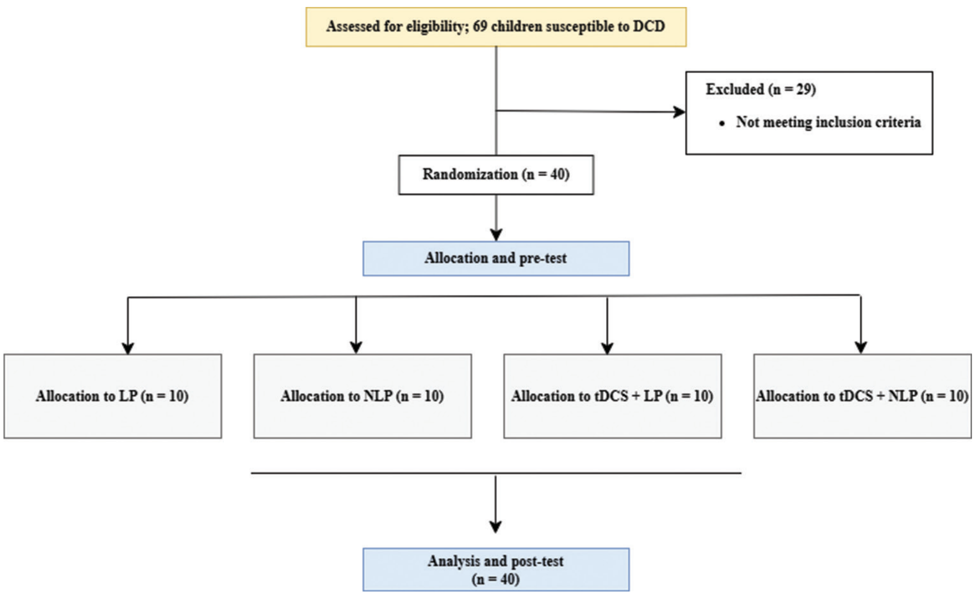

Figure 1. Schematic overview of the research design
Abbreviations: DCD: Developmental coordination disorder; LP: Linear pedagogy; NLP: Non-linear pedagogy; tDCS: Transcranial direct current stimulation.

Table 1. Descriptive information of participants (mean±SD)

Information	LP (2 girls and 8 boys)	NLP (3 girls and 7 boys)	TDCS+LP (2 girls and 8 boys)	TDCS+NLP (1 girl and 9 boys)
Age (year)	8.1±0.7	7.9±0.6	8.2±0.5	8.0±0.8
Weight (kg)	27.5±3.2	26.8±2.9	28.0±3.1	27.2±2.7
High (cm)	128.4±5.6	127.0±6.1	129.2±5.2	128.0±5.8

Abbreviations: LP: Linear pedagogy; NLP: Non-linear pedagogy; SD: Standard deviation; TDCS: Transcranial direct current stimulation.

consent from parents. The exclusion criteria included: (i) Diagnosed neurological or psychological disorders (based on school or parental reports), (ii) an intelligence quotient below 70 (if documented), (iii) uncorrected hearing or visual impairments, and (iv) failure to fully participate in assessment or intervention phases.

2.5. INITIAL ASSESSMENT

In the first phase, children suspected of having DCD were identified through school health records, and 69 children were subsequently screened for eligibility in the second phase. In the second phase, to confirm the diagnosis of DCD, MABC was administered. Only children whose scores fell below the 15th percentile according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) criteria, as supported by previous studies, were selected as the final participants.[3] The MABC is one of the most validated tools for diagnosing DCD. It is designed for children aged 4–16 years. The test is scored based on the child's performance, and the final score is converted into a percentile rank. A score below the 15th percentile indicates a high risk of DCD. The MABC has been widely used in international studies as a clinical reference for diagnosing DCD.[37] The MABC-2 test has demonstrated reliability and validity above 80% in both the original version,[38] and the Turkish version.[39]

Specifically, in the first phase, the children's school health records were reviewed for documented concerns, including repeated reports of motor difficulties from teachers and parents, history of delayed motor milestones, referrals for occupational or physical therapy, and absence of any neurological or intellectual disability diagnoses. While participants did not have a prior formal clinical diagnosis, eligibility was confirmed through a multi-step procedure. In addition to the MABC-2, the other DSM-5 criteria for DCD were considered: (i) Functional impact was verified through teacher and parent reports of difficulties in daily and academic motor tasks, (ii) developmental history confirmed onset of symptoms in early childhood, and (iii) medical records were screened to exclude alternative explanations, such as cerebral palsy, visual impairment, or intellectual disability. Eligibility was confirmed according to DSM-5 diagnostic criteria for DCD.

2.6. MEASUREMENT TOOLS

2.6.1. BRUININKS–OSERETSKY TEST OF MOTOR PROFICIENCY-2 (BOTMP-2)

To evaluate AMC, the BOTMP-2, short form (BOTMP-2SF), developed for 4–21-year-old participants, was used.[40] The BOTMP-2 is a standardized, individually administered test battery that assesses AMC, comprising 53 items in the full version or 14 in the short form. Its maximum total point score (or raw score) is 88, and its standard score range is 20–80. These standardized overall scores were analyzed statistically. The test demonstrated validity and reliability, with a reliability coefficient of 90% for motor skills assessment. The retest reliability coefficients were 0.78 for the long form and 0.86 for the short form.[40,41] Participants were evaluated strictly in accordance with the BOTMP-2SF manual.[41] The four motor-area composite scores were combined into a total motor composite score and converted to an age- and sex-standardized AMC score.

The assessment was conducted indoors in a school gymnasium. Before the actual test, and after length and weight had been measured, hand and foot preferences were determined using a ball-throwing and -kicking task according to the BOTMP-2SF manual. After describing the purpose of each test, supplemented by additional verbal information or a demonstration if necessary, each participant was allowed one trial for each test item. In addition, each test was video recorded from the anterior–posterior and medial–lateral planes. After the test, a total score for each participant was obtained and reported. Two evaluators independently scored each participant during live observation, and from the two data series, interrater reliability was calculated and found to be remarkably high (87.4% agreement).[37,42-44] However, if there was a difference in scores between the first and second evaluators, the first evaluator's score was used for further analysis due to the first evaluator's greater experience and expertise. A third evaluator calculated the point scores from the raw scores for each item, and the overall point score (range: 0–88 points). The second author converted the total point scores into standardized scores (range 20–80) according to the manual guidelines.

2.6.2. PICTORIAL SCALE PERCEIVED MOTOR SKILL COMPETENCE FOR CHILDREN

To assess PMC, the Pictorial Scale of Perceived Motor Skill Competence for Children was used.[45] This tool consists of 13 items and includes two subscales: Locomotor and object control. Each item presents two pictorial representations of a child (a boy or a girl) performing a motor skill. The child selects the picture that most closely resembles themselves, and then, by choosing one of two circles (a large circle indicating high similarity and a small circle indicating low similarity), the evaluator assigns a score between 1 and 4.[3] The total scores range from 12 to 52, with higher scores indicating greater perceived competence. This scoring system was also employed in this study. The administration of this tool was conducted individually for each child by trained evaluators who had previously been trained to work with children, in a quiet environment to allow the child to focus appropriately on the questions. Throughout the administration process, the standardized instructions of the tool were followed. To examine the internal consistency of the instrument, Cronbach's alpha coefficient was calculated for both measurement phases (pre-test and post-test), yielding values between 0.8 and 0.9, indicating satisfactory reliability of the instrument.

2.7. PERCEPTUAL–MOTOR INTERVENTION

The perceptual–motor intervention in this study consisted of 10 training sessions, each lasting 60 min. The overall structure of the sessions included three parts: Warm-up (15 min), main exercises (40 min), and cool-down (5 min). The main exercises involved a variety of activities engaging different aspects of motor and perceptual performance. These activities included walking on a balance beam, standing on a balance board, throwing a ball or a sandbag toward targets at varying distances and heights, stacking plastic cups, arranging dominoes in specific patterns, navigating obstacle courses, reaction-based games, and ball games, such as aiming games or dodgeball. The exercises were designed based on both LP and NLP. This type of intervention was developed and implemented based on previous evidence in children with DCD.[14]

2.8. tDCS INTERVENTION

In this study, as in previous research, tDCS was used for the tDCS intervention groups.[15,16] The target area for stimulation was the right M1, as defined using the international 10–20 system. The anodal (active) electrode, measuring 25 cm^2 and soaked in saline solution, was placed over the right M1 area, and the cathodal (reference) electrode of the same size was placed over the left supraorbital area. The electrodes were secured on the head with special straps. Stimulation was performed using a standard 1 × 1 tDCS device, with the current intensity gradually increasing to 1 mA over 30 s and maintained at that level for 20 min. The stimulation was applied before the motor intervention.

2.9. LP

In the perceptual–motor intervention using the LP, according to previous studies, skills were taught step-by-step following a defined ideal motor pattern. [20,46,47]At the beginning of each activity, the instructor provided detailed explanations of the correct way to perform the movement, the body parts involved, joint positioning, and the sequence of component execution. Then, a model correctly demonstrated the skill. Children were required to imitate this model and practice accordingly. Augmented feedback was provided verbally during or after practice, including corrective or reinforcing points regarding the child's performance. In this method, instructions were typically direct and prescriptive, aimed at aligning the child's performance with the standard model. The environmental conditions and task characteristics were designed to remain constant, with an emphasis on precisely repeating standard movements to reinforce the correct motor pattern.

2.10. NLP

In the perceptual–motor intervention using NLP, based on previous studies, practices were designed according to the ecological dynamics framework by manipulating individual, environmental, and task constraints.[20,46,47] Instead of presenting a specific motor pattern, the instructor only described the general goal of the activity (for example, crossing an obstacle or throwing at a target) and asked the children to reach the goal using their own solutions. In this method, no standard or imitative motor pattern was provided; the focus was on the children's exploration, creativity, and self-discovery of solutions. Direct or prescriptive feedback was eliminated and replaced by indirect instructions, such as altering the environment or task arrangement to guide learning. For instance, if a child improperly used an arm during throwing, a barrier could be introduced, or the target distance could be changed to indirectly encourage the child to adjust their movement technique.

2.11. IMPLEMENTATION METHOD

After selecting eligible participants and obtaining informed consent from parents, the subjects were randomly assigned to four groups (10 participants per group) as described in Section 2.2. Groups 1 and 2 received only the perceptual–motor interventions, whereas Groups 3 and 4 first underwent tDCS brain stimulation in a controlled laboratory environment and then participated in the perceptual–motor exercises later the same day. The tDCS intervention lasted 20 min. These stimulation parameters (1 mA, 20 min, right M1–contralateral supraorbital montage) were selected based on previous pediatric studies demonstrating both safety and effectiveness of this protocol in enhancing motor performance, while minimizing potential side effects.[48] Stimulation was administered by a trained individual, during which the child remained seated and motionless. The motor interventions were conducted by two separate instructors, each holding a master's degree in physical education and specializing in either the LP or NLP. To ensure accurate implementation of the protocols, the research team organized separate training workshops for each instructor before the study, covering both theoretical and practical aspects of their respective methods. In addition, to monitor treatment fidelity, the study authors randomly attended some sessions to assess the alignment of the exercises with the theoretical objectives of the study. All four groups performed the same set of perceptual–motor tasks (e.g., balance, coordination, object control, and locomotor exercises). The only distinction lay in the pedagogical approach: LP emphasized structured, repetitive practice, whereas NLP encouraged variable, adaptive exploration. Thus, the motor content was standardized across groups to ensure comparability, with differences arising solely from instructional style or the addition of tDCS. According to the intervention schedule, three training sessions were held each week (on alternate days). The sessions were organized so that tDCS stimulation was conducted in the morning and motor intervention in the afternoon of the same day, to maximize the potential impact of stimulation on motor learning. In this regard, during the 1st week, on Monday, Group 3 first participated in the tDCS intervention in the morning and then the motor intervention in the afternoon. Subsequently, Group 1 only participated in the motor intervention in the afternoon. On Tuesday, Group 4 received tDCS stimulation in the morning, followed by NLP in the afternoon. Then, Group 2 only participated in the motor intervention. This scheduling pattern was maintained throughout all intervention weeks. Throughout all stages, the instructors were not informed of participants' cognitive conditions, group allocations, and diagnostic information (single-blind design). Furthermore, practice conditions—including session duration, physical environment, equipment, and timing—were kept consistent across all groups to prevent side effects and confounding factors.

2.12. DATA MANAGEMENT AND ANALYSIS

All analyses were performed using Statistical Package for the Social Sciences (SPSS 23.0, IBM Corp., USA). Data are reported as mean ± standard deviation (SD). Normality was assessed using the Shapiro–Wilk test. For primary comparisons, we conducted analyses of covariance (ANCOVAs), using pre-test scores as a covariate, followed by Bonferroni *post hoc* tests ($\alpha = 0.05$). Effect sizes are reported as partial eta-squared (η^2) for ANCOVA.

3. RESULT

No significant differences in AMC and PMC scores were observed between groups at the pre-test ($p>0.05$). To examine group differences in AMC and PMC after controlling for pre-test scores, ANCOVAs were conducted. The ANCOVA results for AMC indicate a significant main effect of group, $F_{(3,35)} = 30.54$, $p<0.001$, $\eta^2_p = 0.724$ (Table 2), suggesting that 72.4% of the variance in post-test AMC scores was explained by the intervention type. Similarly, a significant main effect of group was observed for PMC, $F_{(3,35)} = 4.93$, $p=0.006$, $\eta^2_p = 0.297$ (Table 2), explaining 29.7% of the variance in PMC post-test scores.

Pairwise comparisons (Table 3) for AMC revealed that the NLP and tDCS + NLP outperformed the other groups. Specifically, the tDCS + NLP group showed the highest post-test performance value (mean = 36.48, SD = 1.73). Significant differences were detected between the LP and NLP groups ($p<0.001$, effect size = 3.03) and between the LP and tDCS + NLP groups ($p<0.001$, effect size = 3.16). For PMC, the tDCS + NLP group also exhibited the highest post-test score (mean = 35.75, SD = 5.36). Significant differences were also detected between the LP and NLP groups ($p = 0.034$, effect size = 1.16) and the LP and tDCS + NLP groups ($p=0.003$, effect size = 1.38), and a greater, significant difference was observed between the tDCS + LP and tDCS + NLP groups ($p=0.005$, effect size = 1.23) (Table 3).

Overall, these findings suggest that NLP, particularly when combined with brain stimulation, leads to greater improvements in AMC and PMC compared to LP (Figure 2).

4. DISCUSSION

The aim of this study was to investigate the effects of linear and non-linear perceptual–motor interventions, with or without tDCS, on AMC and PMC in children with DCD. Findings indicated that, regarding AMC, children in

Table 2. Results of analysis of covariance for actual and perceived motor competence

Variables	Sum of squares	df	Mean square	*F*	Sig.	Partial eta squared
AMC (score)						
Pre-test	1.257	1	1.257	0.581	0.451	0.016
Group	198.189	3	66.063	30.540	<0.001	0.724
Error	75.710	35	2.163	75.710		
Total	45258.778	40				
PMC (score)						
Pre-test	1.330	1	1.330	0.078	0.781	0.002
Group	250.614	3	83.538	4.925	0.006	0.297
Error	593.673	35	16.962	593.673		
Total	42187.531	40				

Abbreviations: AMC: Actual motor competence; df: degree of freedom; PMC: Perceived motor competence.

Table 3. Bonferroni *post hoc* tests for actual and perceived motor competence in the post-test

Groups	Mean difference	Standard error	Sig.	95% confidence interval	
				Lower bound	Upper bound
AMC					
LP versus NLP	−3.826*	0.658	<0.001	−5.162	−2.491
LP versus TDCS+LP	−0.347	0.682	0.614	−1.732	1.038
LP versus TDCS+NLP	−5.225*	0.685	<0.001	−6.615	−3.835
NLP versus TDCS+LP	3.479*	0.679	<0.001	2.100	4.859
NLP versus TDCS+NLP	−1.399*	0.682	0.048	−2.782	−0.015
TDCS+LP versus TDCS+NLP	−4.878*	0.658	<0.001	−6.213	−3.542
PMC					
LP versus NLP	4.074*	1.847	0.034	−7.823	−0.324
LP versus TDCS+LP	−0.731	1.902	0.703	−4.593	−4.593
LP versus TDCS+NLP	−6.305*	1.941	0.003	−10.245	−2.364
NLP versus TDCS+LP	3.343	1.873	0.083	−0.459	7.144
NLP versus TDCS+NLP	−2.231	1.902	0.249	−6.092	1.631
TDCS+LP versus TDCS+NLP	−5.573*	1.847	0.005	−9.323	−1.824

Note: *Significant difference, $p<0.05$.
Abbreviations: AMC: Actual motor competence; LP: Linear pedagogy; NLP: Non-linear pedagogy; PMC: Perceived motor competence; TDCS: Transcranial direct current stimulation.

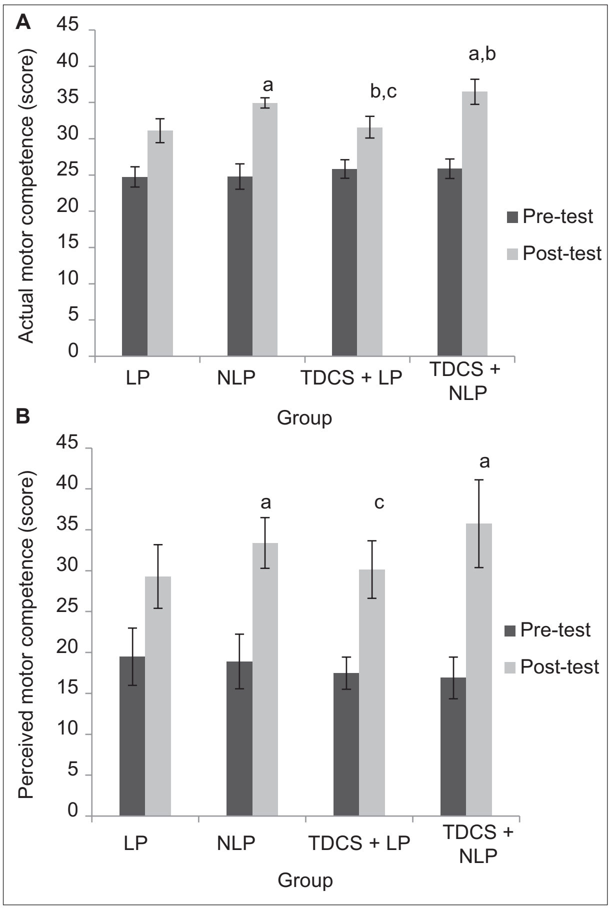

Figure 2. Descriptive information in the pre-test and post-test (A) Actual motor competence. (B) Perceived motor competence.

Notes: [a]Significant versus LP; [b]Significant versus NLP; [c]Significant versus TDCS + NLP.

Abbreviations: LP: Linear pedagogy; NLP: Non-linear pedagogy; TDCS: Transcranial direct current stimulation.

the NLP groups—both with and without tDCS—showed greater improvements compared to those in the LP groups. Furthermore, combining NLP with brain stimulation resulted in superior outcomes compared to LP combined with tDCS. In terms of PMC, the group receiving NLP with tDCS outperformed both LP groups, regardless of whether brain stimulation was present. Although the difference between NLP alone and NLP with tDCS was not statistically significant for perceived competence, the trend favored the combined intervention. These results suggest that educational approaches emphasizing active exploration, particularly when supported by neural facilitation, can significantly enhance both motor performance and self-perception of ability in children with DCD. The results also suggest that the enriched learning environment provided by NLP, together with increased cortical excitability induced by tDCS, creates optimal conditions for motor learning and skill consolidation.

The findings of the present study regarding the effectiveness of perceptual–motor interventions on AMC and PMC align with previous research by Walters[12], De Milander[7], and Tajari *et al.,*[14] all of which reported significant improvements in motor skills among children with DCD following sensory-motor-based interventions. Similarly, the results on brain stimulation interventions are consistent with the findings of Grohs *et al.*[15] and Akremi *et al.,*[16] who demonstrated that tDCS can enhance motor learning and reduce movement errors. However, what distinguishes the present study from previous research is its simultaneous examination of the combined effects of linear and non-linear perceptual–motor interventions alongside tDCS on both AMC and PMC—an approach not specifically addressed in earlier studies. In particular, while supporting the outcomes reported by Mohammadi Orangi *et al.*[28] regarding the superior impact of NLP on children with developmental disorders, this study uniquely extended the evidence by integrating NLP with brain stimulation and demonstrating its superiority over LP. These results highlight the novelty of the present study, which proposes an integrated intervention model that combines educational strategies with neural modulation techniques to holistically enhance the competencies of children with DCD.

In its first focus, the study demonstrated that the type of instructional method plays a pivotal role in enhancing AMC and PMC in children with DCD, with NLP outperforming LP. This superiority likely stems from the inherently flexible, child-centered, and problem-oriented nature of NLP, which enables active exploration and deeper cognitive involvement, thus promoting the development of more resilient and adaptable motor patterns.[20] In contrast to LP—which often confines learners to rigid imitation of pre-established movement templates—NLP encourages trial-and-error learning, self-correction, and creative motor problem-solving.[23] Particularly for children with DCD, who often experience diverse sensory processing and individual limitations, being exposed to varied tasks and environmental constraints fosters the emergence of multiple motor solutions and improves adaptive motor control. Essentially, NLP empowers the child to generate personalized movement strategies rather than conforming to a singular notion of correct movement, thereby reinforcing their sense of motor self-efficacy and agency.[28]

In the second aspect of the study, the role of tDCS in combination with various perceptual–motor training approaches was explored. The results suggested that adding tDCS, particularly when paired with NLP, might have contributed to greater improvements in both AMC and PMC among children than LP and NLP alone. These findings may be attributed to tDCS's effects on enhancing cortical excitability, improving neural network efficiency, and facilitating motor learning processes. It is plausible that pre-training brain stimulation primed the motor system, optimizing encoding processes, enhancing attentional mechanisms, and supporting adaptive adjustments during learning.[8] Moreover, the combination of brain stimulation with the variability and flexibility inherent in NLP might have exposed children to increased motor challenges, enhancing consolidation of motor patterns and promoting positive perceptions of their abilities. Nevertheless, caution is warranted in interpreting these results, as the precise mechanisms underlying the interaction between tDCS and various training methods remain incompletely understood and require further investigation.

One of the main strengths of this study was its innovative and combined design, which simultaneously examined the effects of two perceptual–motor instructional methods (linear and non-linear) along with tDCS on AMC and PMC in children with DCD, thereby proposing a new integrated intervention framework. However, the study also had several limitations. First, although the four-group design with direct comparisons among intervention types largely compensated for this limitation, the absence of an inactive control group may hinder the precise interpretation of intervention effects. Second, the sample size, although determined by an a priori power analysis, remains relatively small. This limits the statistical power to detect smaller effects and constrains the generalizability of the findings to the wider population of children with DCD. Third, no long-term follow-up was conducted to assess the durability of intervention effects, although the primary focus of the study was on immediate post-intervention changes. Fourth, individual differences in response to tDCS (such as prior history of brain stimulation or individual sensitivity) were not directly controlled, although standardization of stimulation intensity and electrode placement was maintained to minimize these effects. Fifth, gender distribution across groups was not fully balanced, with a greater number of boys, which may limit the generalization of findings to girls. Sixth, psychological and emotional variables, such as motivation or anxiety, were not assessed, which could have provided a more comprehensive interpretation of the outcomes; however, the study's focus on motor competence measures was consistent with its primary objectives. Finally, it should be acknowledged that some perceptual–motor intervention tasks share similarities with those assessed by the BOTMP-2, raising the possibility of task-specific practice effects. To mitigate this concern, the intervention program was deliberately designed with diverse activities, variable practice conditions, and an emphasis on exploratory learning rather than direct repetition of test items. This approach aims to reduce test–training overlap and support the interpretation that observed improvements reflect broader motor learning rather than simple practice effects. Nevertheless, future studies should address this issue.

5. CONCLUSION

This study, through its combined four-group design and the application of both perceptual–motor instructional methods and brain stimulation, provided valuable evidence regarding the improvement of AMC and PMC in children with DCD. The findings indicated that NLP, particularly when combined with tDCS, led to greater improvements compared to LP. These results emphasize the importance of enriched, exploratory learning environments and neural facilitation in supporting motor and psychological development in children with motor difficulties. Scientifically, the study introduced an integrated model that can serve as a basis for future research on combining educational and neurophysiological approaches. From a practical perspective, the findings highlight meaningful applications in both educational and clinical settings. For example, teachers and therapists may incorporate NLP into physical education or therapeutic programs to create adaptive learning environments that foster self-efficacy and motivation, whereas the adjunctive use of tDCS may further accelerate learning outcomes. Importantly, the feasibility of implementing NLP in school-based activities or structured therapeutic contexts suggests that the approach is not only theoretically valuable but also applicable in real-world practice. A clearer understanding of how these principles can be scaled and adapted across diverse contexts enhances the generalizability and applied impact of the findings. Nevertheless, future studies with larger samples, longer follow-up periods, and more detailed control of individual differences are recommended to further validate and expand upon these findings.

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CONFLICT OF INTEREST

The authors declare they have no competing interests.

AUTHOR CONTRIBUTIONS

Conceptualization: Altay Ulusoy, Behzad Mohammadi Orangi
Formal analysis: Aref Basereh
Investigation: Altay Ulusoy, Behzad Mohammadi Orangi
Methodology: Altay Ulusoy
Writing–original draft: Behzad Mohammadi Orangi
Writing–review & editing: All authors

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Participation was voluntary, with participants having the right to withdraw at any time without consequences. Participant privacy and confidentiality were respected, and measures were taken to maintain anonymity. Parents of all participants provided written informed consent before the intervention began. The proposed research design was reviewed and approved by the Human Research Ethics Committee of Middle East Technical University under protocol code 0082-ODTUİAEK-2025 before the study was initiated.

CONSENT FOR PUBLICATION

The parents of all participants provided informed consent for the publication of the findings derived from this study.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed in the current study are available upon reasonable request from the corresponding author.

ADDITIONAL DISCLOSURE

The authors wish to state that the translation of the initial manuscript draft from Persian to English was performed using artificial intelligence tools. However, these tools played no role in any other phase of the research, including study design, data collection, analyses, or the final manuscript writing.

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