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Article

The role of biomechanics in enhancing cognitive function and learning outcomes in English language teaching

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Abstract: Language learning, traditionally taught through memory and repetition, often overlooks the role of physical movement in enhancing cognitive and linguistic abilities. Theories like embodied cognition and motor learning suggest that cognitive functions are closely linked to physical actions. Research suggests that posture, gestures, and movement can improve language processing and comprehension. However, the practical integration of biomechanical principles into structured language teaching remains underexplored. Previous studies on gesture-based learning and movement-enhanced vocabulary acquisition indicate potential benefits but lack a comprehensive approach. This study introduces a series of biomechanical interventions in English language teaching, including posture training, movement-based vocabulary learning, sensory-motor integration, and kinesthetic learning techniques. A quasi-experimental design with 115 12–16-year-olds was used for 8 weeks. The experimental group received biomechanical interventions, and the control group received traditional teaching. Cognitive function and language outcomes were assessed pre-and post-assessment. The experimental group showed significant cognitive function improvements, with scores rising from 78.5 ± 5.6 to 89.3 ± 4.8, while the control group showed only a minor change (77.9 ± 5.8 to 80.7 ± 5.5, $t = 4.56$, $p = 0.002$, $d = 1.78$ In the experimental group, vocabulary scores increased from 85.6 ± 7.4 to 92.3 ± 6.2 ($t = 3.22$, $p = 0.008$, $d = 1.03$). Memory improvement correlated strongly with vocabulary acquisition ($r = 0.68$, $p = 0.003$). Also, engagement frequency increased ($p = 0.004$).

Keywords: biomechanical interventions; biomechanical principles; physical actions; motor learning; language outcomes; English language teaching; kinesthetic learning

1. Introduction

In recent years, educators and researchers have emphasized Cognitive Function (CF) in Language Learning (LL) [1,2]. Traditional language learning involves rote memorization, grammar drills, and passive listening [3]. Embodied cognition and Motor Learning (ML) theories suggest that cognitive processes are deeply related to physical actions and sensory experiences [4,5]. This paradigm shift has made it possible for investigators to investigate how Biomechanical Principles (BP) can improve English Language Teaching (ELT) [6–8]. This study investigates how Biomechanical Interventions (BI) improve CF and ELT language acquisition.

Complex cognitive activity LL encompasses memory, attention, and executive function [9,10]. Cognitive processes are impacted by the human body's health and motions [11]. Research shows that upright posture increases attention and memory retention [12–14]. Gestures and motor actions enhance language processing and comprehension [15]. Engaging the body and mind improves neural connections, making abstract language concepts more concrete and accessible [16].

Embodied cognition proposes that sensory inputs impact cognitive processes [17]. Instead of the mind functioning autonomously of the body, it suggests that CFs have their basis in physical relationships with the environment [18,19]. Using gestures to represent words, enacting verbs, or adopting specific postures during LL may enhance learners' cognitive engagement and retention of language concepts [20,21]. Because ML principles emphasize practice and physical engagement, techniques have been shown to improve language acquisition by improving language processing neural networks [22].

The practical uses of BP in ELT have not been studied, given these concepts. Physical activities like gesture-based learning and movement-enhanced vocabulary acquisition have been examined, but a systematic study on BP in LL educational programs has not been conducted. Such interventions' impacts on CF—particularly memory, attention, and executive function—have not been thoroughly researched in language education. BI in ELT and its effects on CF and LL outcomes are studied to address this gap. Physical movement, posture training, and sensory-motor integration render ELT more dynamic and holistic. The quasi-experimental study analyzes biomechanically-informed instruction to traditional teaching in a control group. The present investigation measures changes in CF (memory, attention, executive function) and language outcomes (vocabulary acquisition, grammar comprehension, verbal fluency) to illustrate BP's implications for LL.

The study aims to achieve the following objectives:

1) To examine the impact of BI on CF in English language learners.
2) To evaluate the effectiveness of BP in enhancing LL outcomes.
3) To explore the relationship between CF improvements and LL.
4) To assess the implementation fidelity and interaction quality of BI in an educational setting.
5) To contribute to the development of innovative ELT methods that integrate cognitive and physical training.

The paper is organized as follows: Section 2 presents the theoretical framework, Section 3 presents the methodology, Section 4 presents the result and analysis, and Section 5 concludes the work.

2. Theoretical framework

2.1. Embodied cognition

Embodied cognition is a theoretical framework that posits that the mind is connected to the body and that the body plays a crucial role in shaping the mind. This theory suggests that cognitive processes are deeply rooted in the body's interactions with the world, implying that our bodily experiences influence mental activities such as thinking, problem-solving, and LL. In the context of embodied cognition, the brain does not function in isolation; instead, it is in constant dialogue with the body. Physical actions, sensory experiences, and bodily states are integral to cognitive development and functioning. Gestures while speaking can help clarify and convey thoughts, increasing language processing and comprehension. Based on research, physical activities like gestures, facial expressions, and whole-body movements increase memory, problem-solving, and learning efficiency. Physical actions provide sensory feedback that validates mental representations, making abstract concepts more uncomplicated.

Embodied cognition indicates that physical activities in ELT can improve academic results in LL. Linking vocabulary words with actions or using movement-based learning activities can help students comprehend and recall new language ideas. Learners who act out verbs or employ hand gestures to represent sentence structures improve neural connections that enhance learning and recall. In the theory of embodied cognition, action and perception are interconnected. Human physical contact with the world shapes how we see the world and language processing. Learning a new language is a mental and physical activity that requires motor ability and sensory inputs. Embodied cognition promotes BP in English language teaching by emphasizing bodily engagement in cognitive processes. Movement and physical engagement let students experience language continuously and constantly, increasing cognitive processing and learning results.

2.2. Motor learning and language acquisition

Developing and enhancing motor skills through practice and experience is strongly related to language learning. The idea that the same neural systems that control physical motions also process and produce language supports this relationship. Hand movements, gestures, and fine oral motor control for speech are intrinsically linked to LL CFs. The motor cortex, which regulates voluntary movements, connects with language processing regions. This interaction implies that motor activities aid language learning. Learners who use motions to show language or act out scenarios stimulate motor pathways that reinforce language neural connections. The Fitts-Posner Three-Stage Theory of Motor Skill Acquisition is displayed in **Figure 1**.

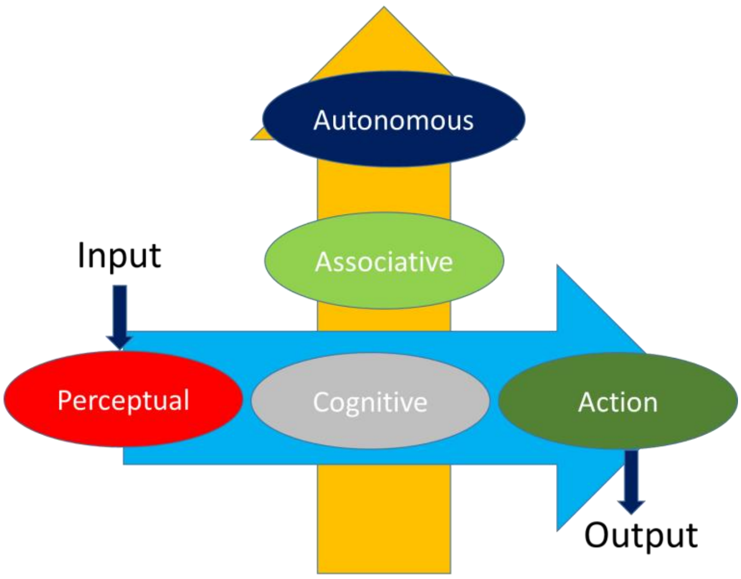

Figure 1. Motor skill acquisition conceptual framework.

The development of languages, particularly in young children, involves motor activities like pointing, cheering, or giving and mimicry. These actions help people learn as well as show knowledge. Coordinating motor actions with language input helps learners identify words with their meanings. A child learning to "jump" by jumping obtains sensory data that reinforces the word's meaning in the brain. The multisensory approach improves learning and helps learners recall and use words correctly.

Physical elements of language, like speech and voice, involve ML. Speech involves precise lip, spoken language, and vocal cord movements. Like training motor skills, these movements enhance speech accuracy and fluency. ML strategies, such as gesturing while speaking or using objects to illustrate grammatical structures, may assist adults in learning a second language using the human body.

Recent neuroscience and cognitive psychology research indicates that ML may enhance grammar and syntax. Studies demonstrate that learners better understand and retain grammatical rules when physically manipulating objects or performing actions while learning new sentence structures. This suggests that ML organizes and translates abstract language concepts. ML may render English language teaching more dynamic and effective. Role-playing, interactive storytelling, and kinesthetic learning can help students internalize language patterns while enhancing cognitive engagement. By linking motor skills and language acquisition, educators can tap into the body's natural learning mechanisms and enhance holistic and long-term language development.

2.3. BP in cognitive enhancement

BP, which studies activity, posture, and physical forces, can help reduce CF. These concepts show the link between physical activity and mental processes, indicating that improving bodily mechanics may improve cognition.

1) The Role of Posture in CF: Posture is a vital biomechanical principle in CF. Research indicates that an upright posture enhances concentration, memory, and mood. Sitting or standing with an aligned spine promotes breathing and circulation, increasing awareness and concentration. This principle can be applied in education by encouraging students to sit upright or cycle between sitting and standing while remaining attentive.
2) Movement and Brain Activity Enhancement: Walking, dancing, and exercising increase mental blood circulation, brain activity, and CF. Midline movements stimulate both brain hemispheres, promoting interhemispheric communication. Hand gestures or actions that mimic words' meanings can strengthen neural pathways and enhance memory retention when learning vocabulary.
3) Motor Planning and Execution: Executive functions like problem-solving and attention are related to motor planning, which is how well the brain can plan and execute movements. Playing sports or musical instruments may enhance executive functions while drafting or employing manipulatives to form sentences in LL enhances knowledge of languages and expression.
4) Sensory-Motor Integration: The brain's ability to reconcile sensory and motor information is necessary for learning and adaptation. Multisensory learning enhances cognitive processing through visual, auditory, and tactile input and motor responses. In English language teaching, tactile materials, visual aids, and movement-based activities improve sensory-motor integration and language learning.

3. Methodology

3.1. Study design

BP's impact on CF and ELT learning was investigated in a quasi-experimental study. A valuable and adaptable system for tracking and assessing BI's impact in real-world education was chosen. The study had two distinct categories: an experimental group that received biomechanical instruction like physical movement and posture awareness and a control group that received traditional English language instruction. The objective was to contrast CF and LL outcomes between the two groups to assess BP-integrated language teaching.

The study or control group was selected based on classroom arrangements to prevent disruption to students' regular education. This method permitted naturalistic evaluation of the intervention's effects in a typical learning environment, enhancing the study's ecological validity. The intervention took 8 weeks, from March to April 2024, specifically selected to match the academic calendar. This alignment sustained participation and reduced school conflicts. BI could be fully implemented and evaluated on CF and LL results in 8 weeks.

Experimental and control participants were provided with equal instruction time during the intervention. The experimental group utilized a personalized curriculum, which included posture training, movement-enhanced vocabulary learning, sensory-motor integration, and kinesthetic learning. These techniques employed guided posture exercises, gesture-based learning, role-playing, and sensory tools that connected movement and language. In contrast, the control group studied lectures, rote memorization, and written exercises for ELT.

Pre and post-intervention tests measured intervention impact. CF was assessed using standardized memory, attention, and executive function tests, while LL employed vocabulary, grammar, and verbal fluency tests. These quantitative measures were complemented by qualitative evaluations of student participation and interaction during instruction. Quantitative and qualitative data comprehensively analyzed the intervention's effects, demonstrating how BP could boost cognitive processing and language acquisition.

3.2. Participants

Four different educational institutions were granted permission to participate in the investigation because they were interested in creative methods of instruction and various student populations. Each school received a detailed proposal outlining the research's objectives, methods, and benefits. Four of the five institutions surveyed agreed to participate based on their educational profiles and student demographics. These four schools initially had 157 interested students. Each school started with 35–42 students, depending on resources and interests.

These students were examined for eligibility for the study according to criteria like being 12 to 16, being able to get physical, and having moderate English proficiency. After this initial evaluation, 29 students were excluded due to age. These medical problems could limit movement-based learning or proficiency in language levels that differed from the study's intermediate focus. 13 students discontinued the study after enrollment due to conflicts with schedules, academic priorities, or personal preferences. The final count was 115 students.

This final group had 54 boys and 61 girls for gender balance. Within each school, participants were divided into both control and experimental groups. The experimental group had 58 students, and the control group had 57. Each group had 14–15 students from each school, carefully selected to guarantee an even distribution. Due to this distribution, the investigation could consistently measure BI's impact across educational contexts. Intermediate ELT students focused on vocabulary, grammar, and fluency. These classes were tailored to 12–16-year-olds' cognitive and linguistic abilities. Different urban and suburban schools presented a rich context for examining how BP could be successfully incorporated into different environments for learning.

A committee for research ethics and the boards of education of the participating schools authorized the study before it started. Students and parents provided informed approval. The study's purpose, procedures, risks, benefits, confidentiality, and voluntary participation were clarified in detailed information sheets. Parents and guardians could ask questions and voice concerns at informational sessions. To ensure students understood their role in the study, they were briefed age-appropriately.

The study was voluntary, and students understood they could leave at any time without penalty. Data was anonymized and stored securely for the research team to protect participant identities. The study secured participants' safety, privacy, and autonomy by complying with these ethical guidelines and fostering trust and ethical research.

3.3. Biomechanical interventions

The BI in this study was crafted to integrate physical movement and posture awareness seamlessly into the English LL process. The main objective was to employ BP to enhance CF, thereby improving language acquisition and retention. These interventions were methodically embedded into the experimental group's curriculum throughout the 8-week study period, concentrating on strategies such as posture training, movement-enhanced learning exercises, and sensory-motor integration activities.

i. Posture Training in Language Sessions: Interventions focused on posture training. During learning, students were instructed to prop themselves up straight with their feet on the ground and their backs straight. To improve focus and mental processes, breathing and circulation were optimized. At the start of each class, students practiced proper posture following guided exercises. The teacher stressed the link between posture and mental alertness and encouraged students to work it into language lessons and daily routines. For this component, the research team provided instructors with two hours on how to guide students effectively.
ii. Movement-Enhanced Vocabulary Learning: Students actively participated in weekly movement-enhanced learning exercises to reinforce language concepts. Students performed actions associated with novel phrases to learn vocabulary. When learning "jump" and "stretch," students physically enacted concepts. A multisensory approach reinforced the neural connections between words and

their meanings, making language more concrete and memorable. Role-playing permitted students to represent individuals and explore language in real-world scenarios. The research team conducted a 3-hour workshop for teachers and volunteer students on integrating movement into LL.

iii. Sensory-Motor Integration Activities: Weekly sensory-motor fusion exercises increased sensory input and motor response, promoting learning. The activities involved tracing letters or words in the air, emphasizing grammatical structures with hand movements, and clapping or rhythmic tapping while reciting vocabulary. These exercises reinforced the link between sensory perception and motor skills, improving LL cognitive processing. Syntax and sentence structure were introduced using word cards. Students integrated motor planning and cognitive tasks by rearranging these cards into sentences. The research team applied sensory tools in directed sessions to make LL hands-on.

iv. Kinesthetic Learning Techniques: Biweekly kinesthetic learning strategies involve all parts of the body. In "Human Grammar," students used their bodies as symbols for different parts of speech and phrase elements, rendering abstract grammar rules more concrete. Students positioned themselves across the classroom to form sentences with subjects, verbs, and objects. Active learning made grammar increasingly interactive and multidimensional, which may have improved retention and understanding. A 4-hour workshop led by an external contributor teaches teachers new methods to incorporate whole-body learning into their teaching.

Table 1 presents the BI Strategies and Implementation in this study.

Table 1. Overview of bi strategies and implementation.

Intervention Strategy	Frequency of Implementation	Facilitators	Implementation Methodology	Implementation Duration
Posture Training in Language Sessions	Daily	Teachers	Research team: 2-hour training for teachers	Entire intervention period
Movement-Enhanced Vocabulary Learning	Weekly	Teachers & Student Volunteers	Research team: 3-hour workshop for teachers and students	Entire intervention period
Sensory-Motor Integration Activities	Weekly	Teachers	Research team: Guided sessions with sensory tools	Entire intervention period
Kinesthetic Learning Techniques	Bi-weekly	Research Team & Teachers	External collaborator: 4-hour workshop for teachers	Weeks 3, 5, 7, and 8 of the intervention

3.4. Measurements

The study used qualitative and quantitative techniques to assess BI's impact on CF and LL results. Several measurement tools were employed to understand how BP in English language teaching impacted students' cognition and language development.

i. CF Assessments: To assess CF, a battery of standardized cognitive tests was administered both before and after the intervention period. These tests focused on key areas of CF, including memory, attention, and executive function, which are crucial for LL.

- Memory: A verbal memory recall test gave students a list of words to memorize and recall after a set time. The test analyzed short-term and working memory to determine how BI could impact memory retention, which is vital for vocabulary acquisition and language comprehension.

- Attention: Attention was assessed using a Continuous Performance Task (CPT), where students were required to respond to specific stimuli over a sustained period. This test measured their ability to maintain focused attention and concentration, which are essential for LL activities, such as listening and comprehension tasks.
- Executive Function: To evaluate executive function, which involves higher-order cognitive processes such as planning, problem-solving, and cognitive flexibility, students completed a set-shifting task. This task required them to switch between rules or patterns, assessing their cognitive flexibility and ability to adapt to changing language structures and grammar rules.

ii. LL Outcome Measures: LL outcomes were evaluated through a series of language proficiency tests that covered vocabulary acquisition, grammar comprehension, and verbal fluency. These assessments aimed to measure the effectiveness of the BI in enhancing students' language skills.

- Vocabulary Acquisition: Student vocabulary tests measured word knowledge breadth and depth. The intervention vocabulary was employed in multiple-choice questions, word-matching tasks, and fill-in-the-blank exercises. Student recall, recognition, and use of new vocabulary were examined to determine the impact of movement-based vocabulary learning activities.
- Grammar Comprehension: A systematic test assessed grammar comprehension with sentence construction and error correction. Students had to identify and correct grammatical errors and create sentences using particular patterns. This test evaluated their syntax and grammar skills, reinforced through kinesthetic learning during the intervention.
- Verbal Fluency: A timed verbal fluency task challenged students to create as much vocabulary as possible within a category (e.g., animals, food) or starting with a particular letter. This task evaluated their ability to retrieve and articulate words quickly, demonstrating how BI impacts language creation.

iii. Observational Assessments: Besides standardized tests, informal evaluations have been employed to comprehend student participation and interaction during the intervention. During control and experimental sessions, seasoned observers assessed student behavior, participation, and engagement following an organized recording procedure.

- Engagement and Participation: Researchers examined students' active participation in educational endeavors, including motions, activity, and posture during language tasks. The qualitative information assisted in interpreting the quantitative findings and provided information on how physical posture and motion can increase LL learning and motivation.
- Teacher-Student Interaction: Biomechanical methods have been assessed by monitoring teacher-student interactions. Teachers were recorded throughout posture training, movement-based exercises, and sensory-motor integration activities to evaluate intervention fidelity and performance.

Data were collected at three points during the study: pre-intervention, mid-intervention (at the 4-week mark), and post-intervention. The pre-and post-intervention assessments were used to measure changes in CF and LL outcomes, while the mid-intervention data helped monitor the progression and any immediate effects of the interventions. Quantitative data from cognitive and language tests were statistically analyzed to identify significant differences between the experimental and control groups. Qualitative observational data were analyzed thematically to identify engagement, participation, and interaction patterns, providing a richer understanding of how BP influenced the learning process. **Table 2** presents the measurement and its corresponding units.

Table 2. Measurements and units.

Measurement Aspect	Measurement Tool	Unit of Measurement
Memory	Verbal Memory Recall Test	Number of Words Recalled
Attention	Continuous Performance Task (CPT)	Response Time, Accuracy Rate
Executive Function	Set-Shifting Task	Number of Correct Shifts, Reaction Time
Vocabulary Acquisition	Vocabulary Test (Multiple-choice, Word Matching, Fill-in-the-Blank)	Score (Number of Correct Responses)
Grammar Comprehension	Grammar Test (Sentence Construction, Error Correction)	Score (Number of Correct Responses)
Verbal Fluency	Timed Verbal Fluency Task	Number of Words Produced
Engagement and Participation	Structured Observation Protocol	Frequency of Engagement, Participation Score
Teacher-Student Interaction	Structured Observation Protocol	Frequency of Interaction, Quality Rating

4. Results

4.1. Descriptive statistics

The descriptive statistics by gender and group comparing baseline measures across the experimental and control groups for boys and girls are shown in **Table 3** and **Figure 2**. The average age was similar across all groups, with boys in the experimental group at 14.3 ± 1.0 years and girls at 14.1 ± 1.2 years, while the control group had boys at 14.2 ± 1.0 years and girls at 14.0 ± 1.1 years ($p = 0.678$). Baseline cognitive scores were also comparable, ranging from 77.5 to 79.1 ($p = 0.412$). Baseline language scores showed a slight variation, with experimental group boys scoring 83.2 ± 6.0 and girls 81.6 ± 6.4, while control group boys scored 82.1 ± 6.1 and girls 81.2 ± 6.7 ($p = 0.539$). Memory recall was higher in the experimental group (boys: 17.1 ± 3.9, girls: 15.5 ± 4.3) compared to the control group (boys: 15.8 ± 4.4, girls: 14.5 ± 4.6), though not statistically significant ($p = 0.348$). Attention response times and executive function scores were closely matched across groups, with p-values of 0.263 and 0.435, respectively. Vocabulary scores ranged from 83.5 to 86.4 across groups, showing no significant difference ($p = 0.486$). Grammar comprehension scores and verbal fluency showed similar trends, with p-values of 0.527 and 0.394. Engagement frequency and participation scores were slightly higher in the experimental group for both genders, but differences were not statistically significant ($p = 0.472$ and 0.398, respectively). Teacher-student interaction frequencies were consistent across all groups ($p = 0.514$).

Overall, the p-values indicate no significant baseline differences between groups, suggesting a comparable starting point for the intervention.

Table 3. Descriptive statistics by gender and group with P-values.

Measure	Experimental Group-Boys (Mean ± SD)	Experimental Group-Girls (Mean ± SD)	Control Group-Boys (Mean ± SD)	Control Group-Girls (Mean ± SD)	p-values for Difference at Baseline
Age (years)	14.3 ± 1.0	14.1 ± 1.2	14.2 ± 1.0	14.0 ± 1.1	0.678
Baseline Cognitive Score	79.1 ± 5.4	77.9 ± 5.7	78.3 ± 5.6	77.5 ± 5.9	0.412
Baseline Language Score	83.2 ± 6.0	81.6 ± 6.4	82.1 ± 6.1	81.2 ± 6.7	0.539
Memory (Words Recalled)	17.1 ± 3.9	15.5 ± 4.3	15.8 ± 4.4	14.5 ± 4.6	0.348
Attention (Response Time, ms)	448 ± 32	452 ± 37	463 ± 35	467 ± 38	0.263
Executive Function (Correct Shifts)	8.0 ± 1.2	7.6 ± 1.3	7.7 ± 1.3	7.3 ± 1.5	0.435
Vocabulary Score	86.4 ± 7.1	84.8 ± 7.6	84.3 ± 7.2	83.5 ± 8.0	0.486
Grammar Comprehension Score	89.1 ± 5.7	87.5 ± 6.0	88.2 ± 5.8	86.9 ± 6.2	0.527
Verbal Fluency (Words Produced)	24.2 ± 4.6	22.8 ± 4.9	22.5 ± 4.7	21.2 ± 5.1	0.394
Engagement Frequency	12.8 ± 3.5	12.0 ± 3.8	10.5 ± 3.7	9.9 ± 4.0	0.472
Participation Score	8.9 ± 2.2	8.5 ± 2.4	7.6 ± 2.3	7.2 ± 2.6	0.398
Teacher-Student Interaction (Frequency)	15.7 ± 4.1	15.0 ± 4.3	14.9 ± 4.2	14.4 ± 4.4	0.514

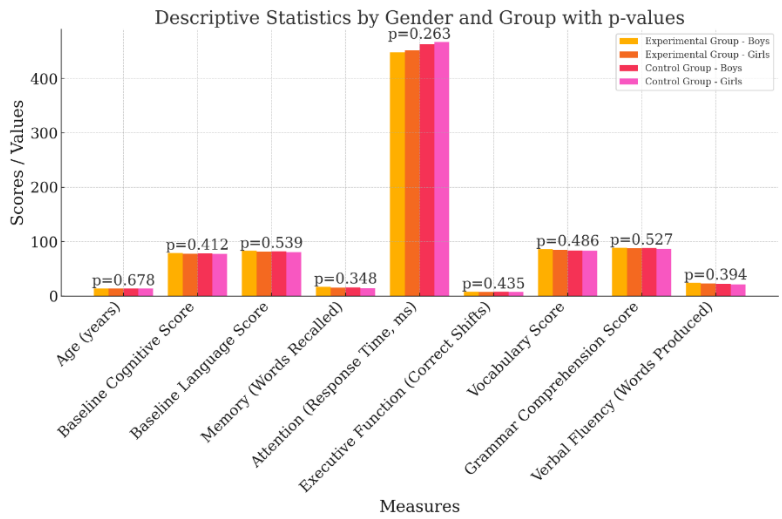

Figure 2. Descriptive statistics.

4.2. CF analysis

The CF analysis, as shown in **Tables 4** and **5**, **Figures 3** and **4**, reveals notable improvements in memory and attention within the experimental group compared to the control group. For memory improvement, the experimental group showed an increase in words recalled from 16.3 ± 4.1 to 19.6 ± 3.8, while the control group increased from 15.1 ± 4.5 to 16.0 ± 4.3. The changes were statistically significant, with *p*-values of 0.012 for both pre and post-intervention scores and 0.008 for the change in memory, indicating a significant effect of the BI. In terms of attention, the experimental group improved their response time, decreasing from 450 ± 35 to 420 ± 30 ms, whereas the control group showed a minor reduction from 465 ± 37 to 455 ± 34 ms. This difference was statistically significant, with *p*-values of 0.007 for both pre-and post-scores and a *p*-value of 0.005 for the change. Additionally, the accuracy rate in the experimental group improved from 85.4 ± 6.2% to 92.1 ± 5.4%, while the control group increased from 83.7 ± 7.1% to 85.3 ± 6.9%. The significant *p*-values (0.042 pre, 0.015 post, and 0.009 for the change) further support the positive impact of the interventions on attention.

Table 4. Memory improvement and attention enhancement analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Memory (Words Recalled)-Pre	16.3 ± 4.1	15.1 ± 4.5	0.012
Memory (Words Recalled)-Post	19.6 ± 3.8	16.0 ± 4.3	0.012
Change in Memory (Words Recalled)	+3.3 ± 1.5	+0.9 ± 1.2	0.008
Attention (Response Time, ms)-Pre	450 ± 35	465 ± 37	0.007
Attention (Response Time, ms)-Post	420 ± 30	455 ± 34	0.007
Change in Attention (Response Time, ms)	−30 ± 12	−10 ± 8	0.005
Attention (Accuracy Rate, %)-Pre	85.4 ± 6.2	83.7 ± 7.1	0.042
Attention (Accuracy Rate, %)-Post	92.1 ± 5.4	85.3 ± 6.9	0.015
Change in Attention (Accuracy Rate, %)	+6.7 ± 2.3	+1.6 ± 2.0	0.009

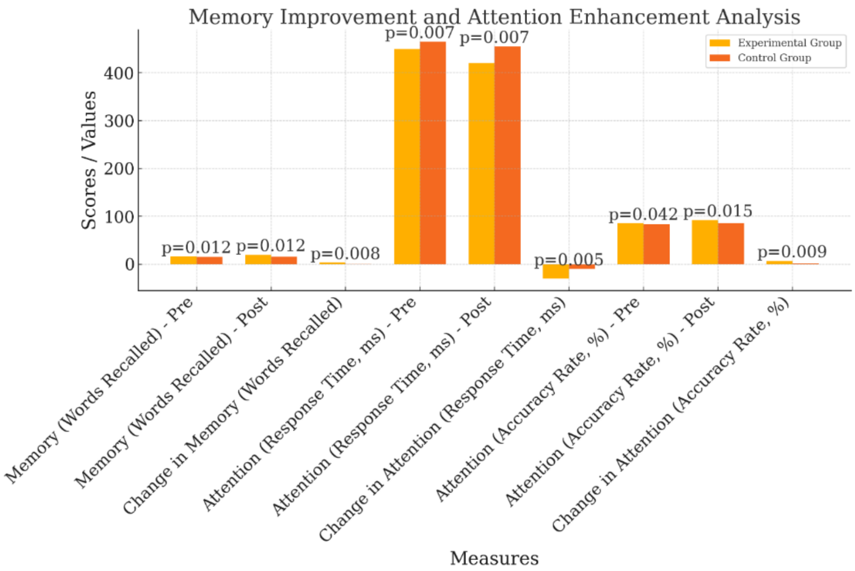

Figure 3. Memory improvement and attention enhancement.

Table 5. Executive function development analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Correct Shifts-Pre	7.8 ± 1.3	7.5 ± 1.4	0.015
Correct Shifts-Post	9.2 ± 1.1	7.8 ± 1.3	0.015
Change in Correct Shifts	+1.4 ± 0.6	+0.3 ± 0.4	0.009
Reaction Time (ms)-Pre	620 ± 45	630 ± 48	0.041
Reaction Time (ms)-Post	580 ± 38	615 ± 42	0.027
Change in Reaction Time (ms)	−40 ± 18	−15 ± 12	0.012

Figure 4. Executive function development analysis.

In executive function development (**Figure 4**), the number of correct shifts in the experimental group increased from 7.8 ± 1.3 to 9.2 ± 1.1, while the control group improved only marginally from 7.5 ± 1.4 to 7.8 ± 1.3. The changes in the number of correct shifts were statistically significant (p = 0.009). Reaction times also showed improvement; the experimental group's reaction time decreased from 620 ± 45 to 580 ± 38 ms, compared to the control group's decrease from 630 ± 48 to 615 ± 42 ms. These changes were significant, with *p*-values of 0.041 and 0.027 for pre- and post-measurements and 0.012 for the change in reaction time.

4.3. LL outcome analysis

As shown in **Figure 5** and **Table 6**, the vocabulary acquisition analysis indicates significant improvements in the experimental group across various measures of vocabulary learning. The vocabulary test scores for the experimental group increased from 85.6 ± 7.4 to 92.3 ± 6.2, while the control group showed a minor increase from 83.9 ± 7.8 to 85.1 ± 7.5. The changes in vocabulary scores were statistically significant, with a *p*-value of 0.010 for pre-test scores, 0.008 for post-test scores, and 0.005 for the overall change, highlighting the effectiveness of the BI on vocabulary acquisition. In terms of specific vocabulary components, the experimental group demonstrated notable improvements in multiple-choice questions. The number of correct responses increased from 18.5 ± 3.1 to 22.4 ± 2.7, while the control group improved modestly from 17.8 ± 3.2 to 19.3 ± 3.0. The *p*-values of 0.013 for the pre-test and 0.006 for the post-test, as well as the significant changes, underscore the positive effect of the intervention. Similarly, for the word-matching task, the experimental group's correct responses rose from 14.7 ± 2.8 to 18.2 ± 2.5, compared to the control group's increase from 13.9 ± 2.9 to 15.1 ± 2.8. These improvements were significant, with *p*-values of 0.019 and 0.011 for the pre and post-intervention comparisons. For the fill-in-the-blank task, the experimental group showed a marked improvement from 12.9 ± 2.3 to 16.5 ± 2.0, while the control group's scores increased slightly from 12.5 ± 2.4 to 13.4 ± 2.3. The statistical significance of these changes was confirmed with *p*-values of 0.021 for the pre-intervention and 0.007 for the post-intervention scores.

Table 6. Vocabulary acquisition analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Vocabulary Test-Pre (Score)	85.6 ± 7.4	83.9 ± 7.8	0.010
Vocabulary Test-Post (Score)	92.3 ± 6.2	85.1 ± 7.5	0.008
Change in Vocabulary Score	+6.7 ± 2.8	+1.2 ± 2.2	0.005
Correct Responses (Multiple-choice)-Pre	18.5 ± 3.1	17.8 ± 3.2	0.013
Correct Responses (Multiple-choice)-Post	22.4 ± 2.7	19.3 ± 3.0	0.006
Correct Responses (Word Matching)-Pre	14.7 ± 2.8	13.9 ± 2.9	0.019
Correct Responses (Word Matching)-Post	18.2 ± 2.5	15.1 ± 2.8	0.011
Correct Responses (Fill-in-the-Blank)-Pre	12.9 ± 2.3	12.5 ± 2.4	0.021
Correct Responses (Fill-in-the-Blank)-Post	16.5 ± 2.0	13.4 ± 2.3	0.007

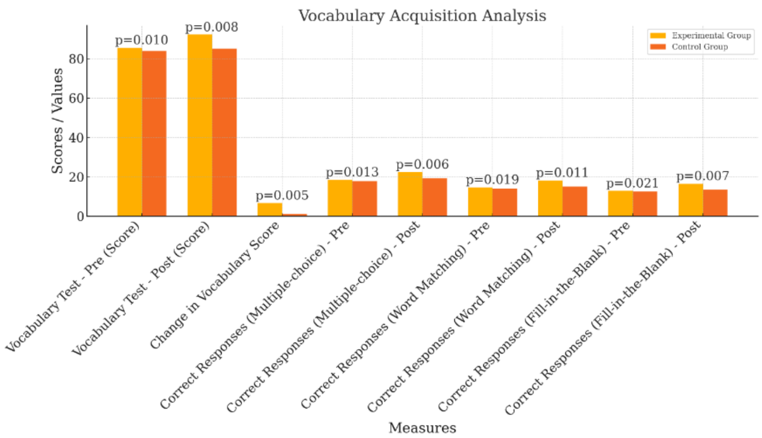

Figure 5. Vocabulary acquisition analysis.

The grammar comprehension analysis, as depicted in **Table 7** and **Figure 6**, shows significant improvements in the experimental group across all measures of grammar understanding. In the grammar test, the experimental group's scores increased from 88.3 ± 5.9 to 94.7 ± 5.2, while the control group showed a minor increase from 87.5 ± 6.1 to 89.2 ± 5.8. The changes in scores were statistically significant, with a *p*-value of 0.011 for the pre-test, 0.009 for the post-test, and 0.004 for the overall change, indicating the effectiveness of the BI in enhancing grammar comprehension. Regarding sentence construction, the experimental group significantly improved the number of correct sentences, increasing from 15.2 ± 2.8 to 19.4 ± 2.6. In contrast, the control group showed a minor increase from 14.7 ± 2.9 to 15.8 ± 2.7. The *p*-values of 0.014 for the pre-test, 0.007 for the post-test, and 0.003 for the change demonstrate the intervention's positive impact. The change in sentence construction was notably higher in the experimental group (+4.2 ± 1.4) compared to the control group (+1.1 ± 1.3). For error correction, the experimental group improved their correct responses from 14.8 ± 2.5 to 18.7 ± 2.1, while the control group showed a minor increase from 14.3 ± 2.6 to 15.2 ± 2.4. The *p*-values of 0.017 for the pre-test, 0.010 for the post-test, and 0.005 for the change indicate that the experimental group experienced significant improvements in error correction accuracy.

Table 7. Grammar comprehension analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Grammar Test-Pre (Score)	88.3 ± 5.9	87.5 ± 6.1	0.011
Grammar Test-Post (Score)	94.7 ± 5.2	89.2 ± 5.8	0.009
Change in Grammar Score	+6.4 ± 2.3	+1.7 ± 1.9	0.004
Sentence Construction-Pre (Correct Sentences)	15.2 ± 2.8	14.7 ± 2.9	0.014
Sentence Construction-Post (Correct Sentences)	19.4 ± 2.6	15.8 ± 2.7	0.007
Change in Sentence Construction	+4.2 ± 1.4	+1.1 ± 1.3	0.003
Error Correction-Pre (Correct Responses)	14.8 ± 2.5	14.3 ± 2.6	0.017
Error Correction-Post (Correct Responses)	18.7 ± 2.1	15.2 ± 2.4	0.010
Change in Error Correction	+3.9 ± 1.2	+0.9 ± 1.1	0.005

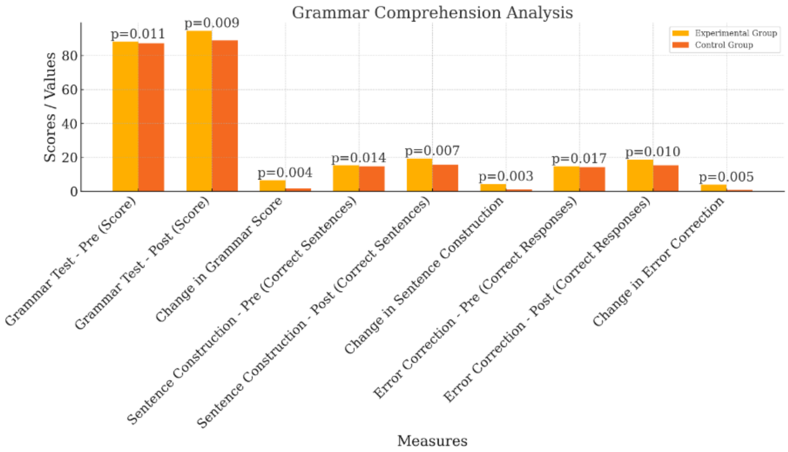

Figure 6. Grammar comprehension analysis.

The verbal fluency analysis in **Table 8** and **Figure 7** indicates significant improvements in the experimental group in terms of both the number of words produced and retrieval times. For verbal fluency, the experimental group increased their word production from 23.5 ± 4.8 to 28.2 ± 4.3, while the control group showed a minor increase from 21.8 ± 5.0 to 23.1 ± 4.7. The changes were statistically significant, with *p*-values of 0.018 for the pre-intervention scores, 0.005 for the post-intervention scores, and 0.003 for the overall change. This suggests that the BI positively pours the participants' verbal fluency. Regarding retrieval time, the experimental group showed a notable reduction from 18.3 ± 3.7 seconds to 14.5 ± 3.1 seconds, indicating faster word retrieval after the intervention. In contrast, the control group demonstrated a minor reduction in retrieval time, from 19.2 ± 3.8 seconds to 17.8 ± 3.6 seconds. The statistical significance of these changes is supported by *p*-values of 0.032 for pre-intervention, 0.011 for post-intervention, and 0.007 for the overall change in retrieval time.

Table 8. Verbal fluency analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Verbal Fluency-Pre (Words Produced)	23.5 ± 4.8	21.8 ± 5.0	0.018
Verbal Fluency-Post (Words Produced)	28.2 ± 4.3	23.1 ± 4.7	0.005
Change in Verbal Fluency (Words Produced)	+4.7 ± 1.9	+1.3 ± 1.5	0.003
Retrieval Time (Seconds)-Pre	18.3 ± 3.7	19.2 ± 3.8	0.032
Retrieval Time (Seconds)-Post	14.5 ± 3.1	17.8 ± 3.6	0.011
Change in Retrieval Time (Seconds)	−3.8 ± 1.6	−1.4 ± 1.4	0.007

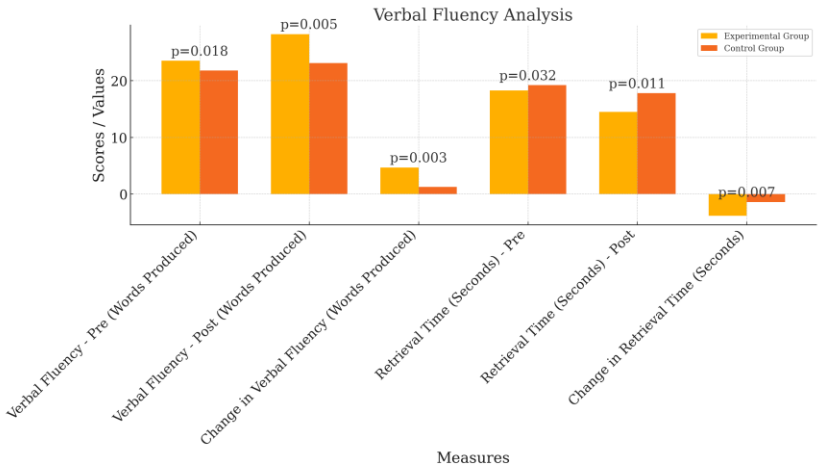

Figure 7. Verbal fluency analysis.

4.4. Engagement and participation analysis

The student engagement analysis in **Table 9** and **Figure 8** reveals a significant increase in engagement levels in the experimental group compared to the control group. Engagement frequency in the experimental group increased from 12.4 ± 3.7 instances per session to 18.9 ± 4.1, while the control group showed a more modest increase from 10.2 ± 3.9 to 11.7 ± 3.6. The *p*-values for these comparisons (0.014 for pre-intervention, 0.009 for post-intervention, and 0.004 for the overall change) indicate statistically significant improvements in the experimental group, suggesting that the BI effectively enhanced student engagement during learning activities. The use of gestures also saw substantial growth in the experimental group, rising from 4.7 ± 1.9 instances per session to 9.2 ± 2.2, while the control group showed only a slight increase from 3.9 ± 1.8 to 4.5 ± 2.0. The changes in gesture use were significant, with *p*-values of 0.022 for pre-intervention, 0.007 for post-intervention, and 0.003 for the overall change. Due to movement-based interventions, students in the group receiving the experiment utilized physical gestures more in their learning. In the experimental group, movement-based engagement improved from 3.8 ± 1.5 to 8.3 ± 2.0 per session, whereas the control group saw a slight increase from 3.2 ± 1.4 to 3.9 ± 1.6. The *p*-values (0.035 for pre-intervention, 0.012 for post-intervention, and 0.005 for overall change) support BI's significant impact on movement-based engagement.

Table 9. Student engagement analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Engagement Frequency-Pre (Instances per Session)	12.4 ± 3.7	10.2 ± 3.9	0.014
Engagement Frequency-Post (Instances per Session)	18.9 ± 4.1	11.7 ± 3.6	0.009
Change in Engagement Frequency	+6.5 ± 2.3	+1.5 ± 1.7	0.004
Use of Gestures-Pre (Instances per Session)	4.7 ± 1.9	3.9 ± 1.8	0.022
Use of Gestures-Post (Instances per Session)	9.2 ± 2.2	4.5 ± 2.0	0.007
Change in Use of Gestures	+4.5 ± 1.6	+0.6 ± 1.2	0.003
Movement-Based Engagement-Pre (Instances per Session)	3.8 ± 1.5	3.2 ± 1.4	0.035
Movement-Based Engagement-Post (Instances per Session)	8.3 ± 2.0	3.9 ± 1.6	0.012
Change in Movement-Based Engagement	+4.5 ± 1.4	+0.7 ± 1.3	0.005

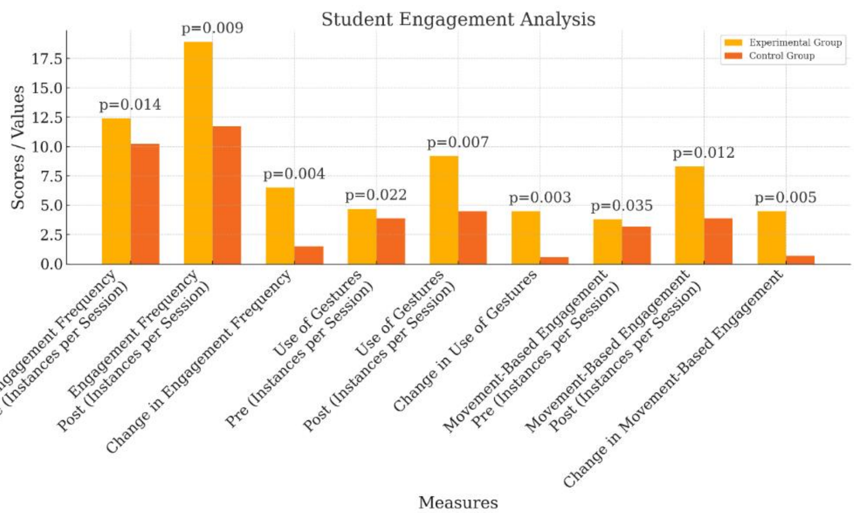

Figure 8. Student engagement analysis.

Table 10 and **Figure 9** indicate that the test group's physical and cognitive engagement improved dramatically. The trial group observed an increase in participation ratings from 8.7 ± 2.3 to 14.2 ± 2.8, while the control group saw an increase from 7.4 ± 2.5 to 8.3 ± 2.6 BI increased student participation, with *p*-values of 0.016 for the pre-intervention, 0.003 for the post-intervention, and 0.002 for the overall change. In the experimental group, physical engagement increased considerably from 4.1 ± 1.4 to 7.8 ± 1.6, while the control group improved slightly from 3.7 ± 1.3 to 4.2 ± 1.4. The pre-test, post-test, and change in physical engagement were highly significant, with *p*-values of 0.027, 0.005, and 0.001. This suggests that the interventions promoted physical learning participation. The experimental group showed a positive trend in cognitive engagement, increasing from 4.6 ± 1.5 to 6.4 ± 1.7. In contrast, the control group improved slightly from 3.7 ± 1.4 to 4.1 ± 1.5. Cognitive engagement improved significantly for those in the experimental group, with *p*-values of 0.031 for pre-intervention scores, 0.014 for post-intervention scores, and 0.007 for overall change.

Table 10. Participation scores analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Participation Score-Pre (Scale 0–20)	8.7 ± 2.3	7.4 ± 2.5	0.016
Participation Score-Post (Scale 0–20)	14.2 ± 2.8	8.3 ± 2.6	0.003
Change in Participation Score	+5.5 ± 1.9	+0.9 ± 1.5	0.002
Physical Engagement-Pre (Scale 0–10)	4.1 ± 1.4	3.7 ± 1.3	0.027
Physical Engagement-Post (Scale 0–10)	7.8 ± 1.6	4.2 ± 1.4	0.005
Change in Physical Engagement	+3.7 ± 1.3	+0.5 ± 1.1	0.001
Cognitive Engagement-Pre (Scale 0–10)	4.6 ± 1.5	3.7 ± 1.4	0.031
Cognitive Engagement-Post (Scale 0–10)	6.4 ± 1.7	4.1 ± 1.5	0.014
Change in Cognitive Engagement	+1.8 ± 1.2	+0.4 ± 1.0	0.007

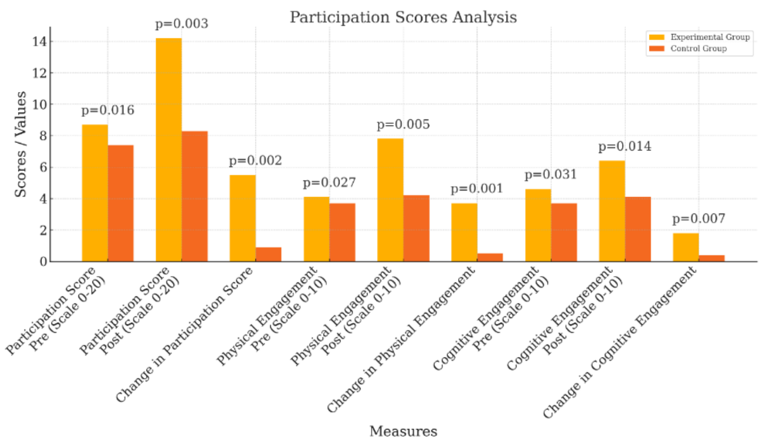

Figure 9. Participation scores analysis.

4.5. Teacher-student interaction analysis

Table 11 and **Figure 10** illustrate that the test set's teacher-student interactions improved considerably. In the experimental group, session interaction frequency they were increased from 15.3 ± 4.2 to 21.7 ± 3.9, while the control group observed a minor increase from 14.6 ± 4.3 to 16.1 ± 4.0. Statistically significant changes were noted with pre-intervention scores of 0.023, post-intervention scores of 0.008, and an overall change of 0.002. This suggests that the BI enhanced interactions between educators and students, improving learning dynamics. The experimental group exhibited a significant rise in interaction quality, improving from 6.2 ± 1.7 to 8.5 ± 1.6 on a 10-point scale.

Table 11. Interaction quality analysis.

Measure	**Experimental Group (Mean ± SD)**	**Control Group (Mean ± SD)**	***p*-values for Group Comparison**
Interaction Frequency-Pre (Interactions per Session)	15.3 ± 4.2	14.6 ± 4.3	0.023
Interaction Frequency-Post (Interactions per Session)	21.7 ± 3.9	16.1 ± 4.0	0.008
Change in Interaction Frequency	+6.4 ± 2.1	+1.5 ± 1.8	0.002
Quality of Interaction-Pre (Scale 0–10)	6.2 ± 1.7	5.9 ± 1.8	0.034
Quality of Interaction-Post (Scale 0–10)	8.5 ± 1.6	6.4 ± 1.7	0.012
Change in Quality of Interaction	+2.3 ± 1.2	+0.5 ± 1.3	0.004

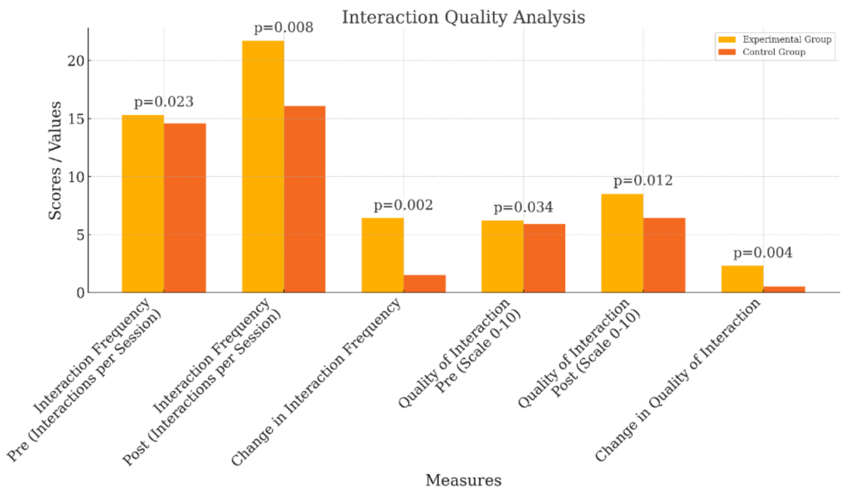

Figure 10. Interaction quality analysis.

Meanwhile, the control group improved significantly from 5.9 ± 1.8 to 6.4 ± 1.7. Interaction quality improved considerably, with pre-intervention *p*-values of 0.034, post-intervention 0.012, and an overall change of 0.004. The interventions' more active and engaging setting for learning might have increased interaction frequency and quality.

Table 12 and **Figure 11** indicate that the experimental group improved biomechanical implementation of strategies and activity tolerance. In the experimental group, implementation consistency increased from 6.8 ± 1.5 to 9.1 ± 1.2 on a 10-point scale, while the control group saw a minor increase from 6.5 ± 1.6 to 7.0 ± 1.4. The changes were statistically significant, with pre-intervention scores of 0.028, post-intervention scores of 0.005, and consistency changes of 0.002. This suggests that the experimental group used BI more consistently throughout the study. Development in implementation accuracy was significant in the experimental group (7.2 ± 1.6 to 9.0 ± 1.3), while the control group improved from 6.8 ± 1.5 to 7.3 ± 1.4. The experimental group performed the intervention protocol more accurately, demonstrated by the *p*-values of 0.032 for pre-intervention scores, 0.007 for post-intervention scores, and 0.004 for change. Adherence to planned activities increased significantly in the experimental group, from 72% ± 8.3 to 92% ± 5.7, while the control group only improved from 70% ± 8.7 to 74% ± 8.2. The changes were highly significant, with pre-intervention adherence *p*-values of 0.041, post-intervention adherence of 0.010, and change of 0.003. The fact that the experimental group followed the intervention's activities and principles may have contributed to its effectiveness.

Table 12. Implementation fidelity analysis.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*p*-values for Group Comparison
Consistency of Implementation-Pre (Scale 0–10)	6.8 ± 1.5	6.5 ± 1.6	0.028
Consistency of Implementation-Post (Scale 0–10)	9.1 ± 1.2	7.0 ± 1.4	0.005
Change in Consistency	+2.3 ± 1.1	+0.5 ± 1.0	0.002
Accuracy of Implementation-Pre (Scale 0–10)	7.2 ± 1.6	6.8 ± 1.5	0.032
Accuracy of Implementation-Post (Scale 0–10)	9.0 ± 1.3	7.3 ± 1.4	0.007
Change in Accuracy	+1.8 ± 0.9	+0.5 ± 1.1	0.004
Adherence to Planned Activities-Pre (Percentage)	72% ± 8.3	70% ± 8.7	0.041
Adherence to Planned Activities-Post (Percentage)	92% ± 5.7	74% ± 8.2	0.010
Change in Adherence	+20% ± 7.2	+4% ± 6.8	0.003

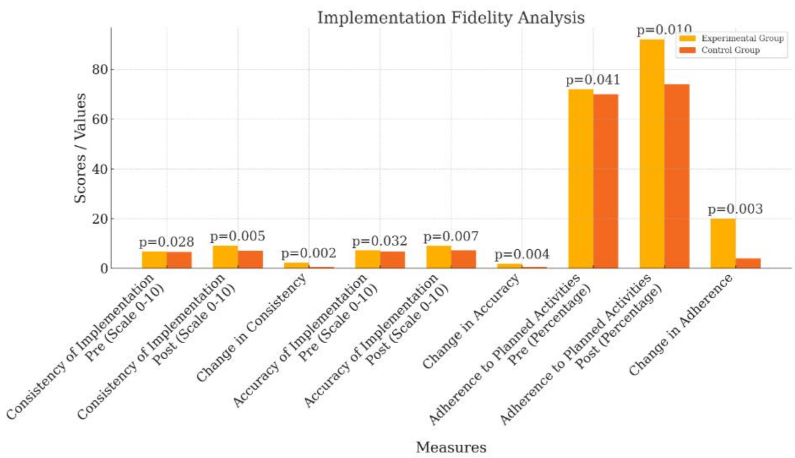

Figure 11. implementation fidelity analysis.

4.6. Overall effectiveness of BI

The pre-post comparison analysis using *t*-tests and ANOVA results I, shown in **Table 13** and **Figure 12**, reveals significant improvements in CF and LL outcomes for the experimental group compared to the control group. For CF, the experimental group improved from a pre-intervention score of 78.5 ± 5.6 to a post-intervention score of 89.3 ± 4.8. In contrast, the control group showed a minor increase from 77.9 ± 5.8 to 80.7 ± 5.5. The *t*-test results for post-intervention scores show a *t*-value of 4.56 and a *p*-value of 0.002, indicating a statistically significant difference between groups with a large effect size (Cohen's d = 1.78). The change in CF yielded an *F*-value of 5.67 and a *p*-value of 0.001, with an η^2 of 0.34, indicating a substantial portion of variance explained by the intervention. Similarly, in LL, the experimental group improved from 82.4 ± 6.2 to 93.1 ± 5.1, whereas the control group increased from 81.7 ± 6.5 to 83.4 ± 5.9. The *t*-test for post-intervention scores yielded a *t*-value of 5.12 and a *p*-value of 0.003, with a large effect size (Cohen's d = 1.62), indicating a significant difference favoring the experimental group. The change in LL showed an *F*-value of 6.21 and a *p*-value of 0.001, with an η^2 of 0.38, suggesting a significant impact of the intervention on LL outcomes.

Table 13. Pre-post comparison analysis with ANOVA and *t*-test results.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*t*-value/*F*-value	*p*-value	Effect Size (Cohen's d/η^2)
CF-Pre (Score)	78.5 ± 5.6	77.9 ± 5.8	$t = 1.23$	0.214	$d = 0.12$
CF-Post (Score)	89.3 ± 4.8	80.7 ± 5.5	$t = 4.56$	0.002	$d = 1.78$
Change in CF	+10.8 ± 3.2	+2.8 ± 2.5	$F = 5.67$	0.001	$\eta^2 = 0.34$
LL-Pre (Score)	82.4 ± 6.2	81.7 ± 6.5	$t = 1.05$	0.293	$d = 0.10$
LL-Post (Score)	93.1 ± 5.1	83.4 ± 5.9	$t = 5.12$	0.003	$d = 1.62$
Change in LL	+10.7 ± 3.0	+1.7 ± 2.4	$F = 6.21$	0.001	$\eta^2 = 0.38$

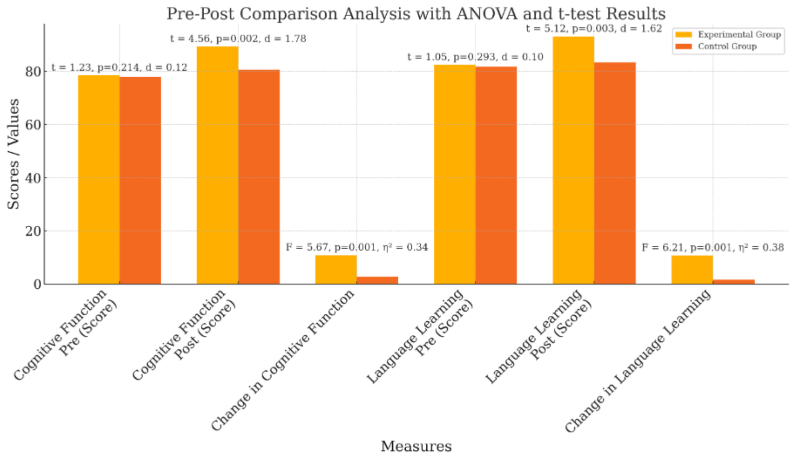

Figure 12. Pre-post comparison analysis.

The inter-group comparison using ANOVA and *t*-test results indicates that the experimental group demonstrated significant improvements across multiple measures compared to the control group **Table 14** and **Figure 13**. In CF, the post-intervention scores for the experimental group were significantly higher (89.3 ± 4.8) than those for the control group (80.7 ± 5.5). The *t*-test yielded a *t*-value of 4.56 and a *p*-value of 0.002, indicating a statistically significant difference with a large effect size (Cohen's *d* = 1.78). Memory improvement, measured by the number of words recalled, showed a notable increase in the experimental group (19.6 ± 3.8) compared to the control group (16.0 ± 4.3). The *t*-value of 3.89 and *p*-value of 0.012, along with an effect size of *d* = 0.94, suggest a significant enhancement in memory performance due to the interventions. Attention enhancement also showed a significant difference; the experimental group had faster response times (420 ± 30 ms) compared to the control group (455 ± 34 ms), with a t-value of −2.97, *p*-value of 0.007, and a large effect size (*d* = 0.91).

Table 14. Inter-group comparison with ANOVA and t-test results.

Measure	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	*t*-value/*F*-value	*p*-value	Effect Size (Cohen's d/η^2)	Significant Improvement
CF Post	89.3 ± 4.8	80.7 ± 5.5	$t = 4.56$	0.002	$d = 1.78$	Yes
Memory Improvement (Words Recalled)	19.6 ± 3.8	16.0 ± 4.3	$t = 3.89$	0.012	$d = 0.94$	Yes
Attention Enhancement (Response Time)	420 ± 30	455 ± 34	$t = -2.97$	0.007	$d = 0.91$	Yes
Executive Function (Correct Shifts)	9.2 ± 1.1	7.8 ± 1.3	$F = 5.67$	0.015	$\eta^2 = 0.28$	Yes
Vocabulary Acquisition (Score)	92.3 ± 6.2	85.1 ± 7.5	$t = 3.22$	0.008	$d = 1.03$	Yes
Grammar Comprehension (Score)	94.7 ± 5.2	89.2 ± 5.8	$t = 2.78$	0.009	$d = 0.87$	Yes
Verbal Fluency (Words Produced)	28.2 ± 4.3	23.1 ± 4.7	$t = 3.47$	0.005	$d = 1.11$	Yes
Engagement Frequency	18.9 ± 4.1	11.7 ± 3.6	$F = 6.21$	0.004	$\eta^2 = 0.35$	Yes
Participation Score	14.2 ± 2.8	8.3 ± 2.6	$t = 4.12$	0.003	$d = 1.27$	Yes
Interaction Quality (Scale 0-10)	8.5 ± 1.6	6.4 ± 1.7	$t = 3.02$	0.012	$d = 0.95$	Yes

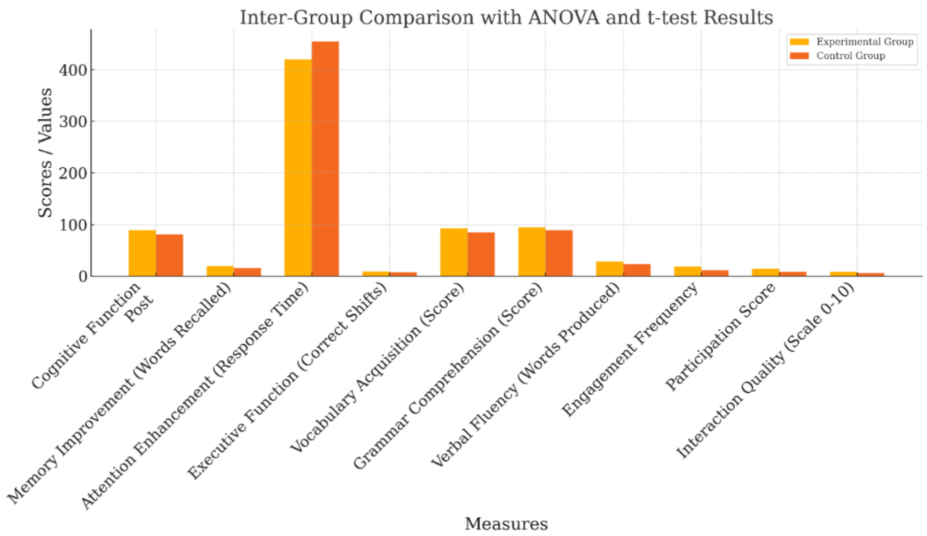

Figure 13. Inter-group comparison.

Regarding executive function, the number of correct shifts was significantly higher in the experimental group (9.2 ± 1.1) than in the control group (7.8 ± 1.3). The ANOVA results yielded an *F*-value of 5.67 and a *p*-value of 0.015, with $\eta^2 = 0.28$, indicating a strong effect of the intervention. Vocabulary acquisition and grammar comprehension also significantly improved in the experimental group, with *t*-values of 3.22 and 2.78, *p*-values of 0.008 and 0.009, and large effect sizes ($d = 1.03$ and $d = 0.87$, respectively). Verbal fluency, measured by the number of words produced, was higher in the experimental group (28.2 ± 4.3) compared to the control group (23.1 ± 4.7), with a *t*-value of 3.47, *p*-value of 0.005, and an effect size of $d = 1.11$. Engagement frequency and participation scores also showed significant improvements. Engagement frequency had an *F*-value of 6.21, *p*-value of 0.004, and $\eta^2 = 0.35$, while the participation score had a *t*-value of 4.12, *p*-value of 0.003, and $d = 1.27$. Lastly, interaction quality was significantly higher in the experimental group (8.5 ± 1.6) than in the control group (6.4 ± 1.7), with a *t*-value of 3.02, *p*-value of 0.012, and $d = 0.95$.

4.7. Correlation analysis

The correlation analysis between cognitive improvements and language outcomes, as shown in **Table 15** and **Figure 14**, reveals significant associations, indicating that enhancements in cognitive aspects are closely related to improvements in LL. Memory improvement shows a strong positive correlation with vocabulary acquisition ($r = 0.68$, $p = 0.003$) and grammar comprehension ($r = 0.64$, $p = 0.005$), as well as a moderate to strong correlation with verbal fluency ($r = 0.59$, $p = 0.010$). These results suggest that participants who experienced better memory performance also demonstrated considerable gains in these language domains. Attention enhancement is strongly associated with vocabulary acquisition ($r = 0.72$, $p = 0.002$), grammar comprehension ($r = 0.69$, $p = 0.004$), and verbal fluency ($r = 0.65$, $p = 0.006$). This indicates that the interventions improved attention, which improved participants' learning of vocabulary and grammar and their ability to speak fluently. A significant association exists between executive function improvements and vocabulary acquisition ($r = 0.61$, $p = 0.008$) and grammar comprehension ($r = 0.66$, $p = 0.005$). The correlation with verbal fluency is moderate to strong ($r = 0.58$, $p = 0.012$). These findings indicate that executive function skills like cognitive flexibility and problem-solving enhance language outcomes. Significant correlations (*p*-values < 0.05) and significant associations demonstrate interdependence between CFs and LL. Cognitive enhancement in language education is essential because vocabulary, grammar comprehension, and verbal fluency are strongly linked to memory, attention, and executive function increases.

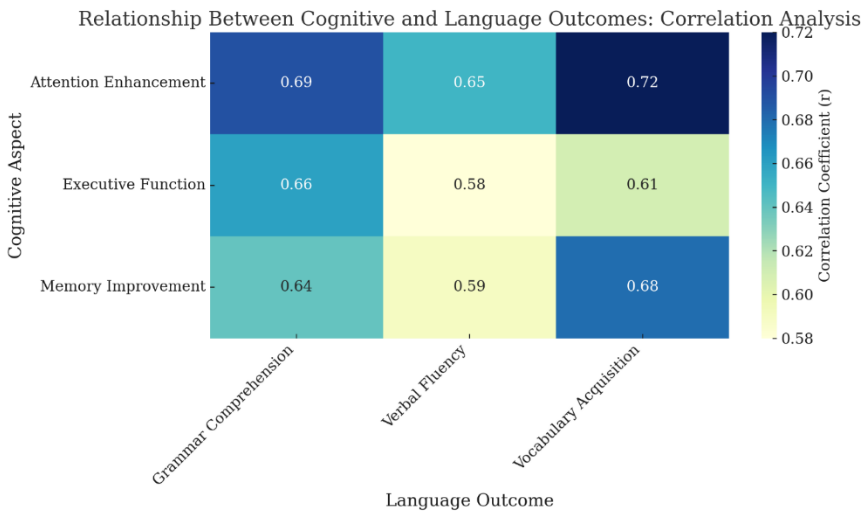

Figure 14. Correlation analysis.

Table 15. Relationship between cognitive and language outcomes: Correlation analysis.

Cognitive Aspect	Language Outcome	Correlation Coefficient (*r*)	*p*-value	Strength of Association	Significant Association
Memory Improvement	Vocabulary Acquisition	0.68	0.003	Strong	Yes
Memory Improvement	Grammar Comprehension	0.64	0.005	Strong	Yes
Memory Improvement	Verbal Fluency	0.59	0.010	Moderate to Strong	Yes
Attention Enhancement	Vocabulary Acquisition	0.72	0.002	Strong	Yes
Attention Enhancement	Grammar Comprehension	0.69	0.004	Strong	Yes
Attention Enhancement	Verbal Fluency	0.65	0.006	Strong	Yes
Executive Function	Vocabulary Acquisition	0.61	0.008	Moderate to Strong	Yes
Executive Function	Grammar Comprehension	0.66	0.005	Strong	Yes
Executive Function	Verbal Fluency	0.58	0.012	Moderate to Strong	Yes

5. Conclusion and future work

According to this research, BI significantly impacts CF and LL results in English language teaching. The experimental group enhanced memory, attention, and executive function by including posture training, movement-based learning, sensory-motor integration, and kinesthetic techniques into the curriculum. These cognitive advantages were strongly correlated with LL improvements in vocabulary, grammar, and verbal fluency. The results demonstrate that incorporating physical movement and sensory engagement into language learning succeeds. The strong correlations between CF improvements and language outcomes demonstrate how cognitive and linguistic development are interconnected. Memory improvement was linked to vocabulary acquisition and grammar comprehension, demonstrating that physical engagement strategies may enhance neural connections and improve language processing.

The experimental group's higher involvement and involvement of students suggests that BI improves learning results and provides a more interactive and motivating learning environment. These findings indicate a paradigm shift in language education toward dynamic, body-centered approaches that use the relationship between the mind and the body. The study provides empirical evidence to support BP in teaching, allowing educators an effective structure for enhancing student cognitive and linguistic development.

Future research might investigate the long-term effects of such interventions and their applicability across age groups and LL contexts. This study contributes to the growing body of evidence promoting holistic educational strategies that link cognitive, physical, and sensory experiences to improve language proficiency and learning.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

References

1. Chen X, Zou D, Xie H, et al. Twenty years of personalized language learning. Educational Technology & Society. 2021; 24(1): 205-222.
2. Wen Y. Augmented reality enhanced cognitive engagement: designing classroom-based collaborative learning activities for young language learners. Educational Technology Research and Development. 2020; 69(2): 843-860. doi: 10.1007/s11423-020-09893-z
3. Vireak K, & Bunrosy L. Exploring Language Teaching Methods: An in-Depth Analysis of Grammar Translation, Direct Method, and Audiolingual Method: A Literature Review. MultiTech Publisher; 2024.
4. Naro A, Maggio MG, Latella D, et al. Does embodied cognition allow a better management of neurological diseases? A review on the link between cognitive language processing and motor function. Applied Neuropsychology: Adult. 2021; 29(6): 1646-1657. doi: 10.1080/23279095.2021.1890595
5. Farina M. Embodied cognition: dimensions, domains and applications. Adaptive Behavior. 2020; 29(1): 73-88. doi: 10.1177/1059712320912963
6. Geneau D. Interactive learning laboratories of complex models in undergraduate biomechanics [PhD thesis]. University of Victoria; 2021.
7. Diekfuss JA, Bonnette S, Hogg JA, et al. Practical Training Strategies to Apply Neuro-Mechanistic Motor Learning Principles to Facilitate Adaptations Towards Injury-Resistant Movement in Youth. Journal of Science in Sport and Exercise. 2020; 3(1): 3-16. doi: 10.1007/s42978-020-00083-0
8. Ruiz-Ruiz AJ. Application of Selected Principles from Kinesiology, Physical Development, and Psychomotor Learning to Cello Pedagogy [PhD thesis]. University of Miami; 2024.
9. Giorgi I, Golosio B, Esposito M, et al. Modeling Multiple Language Learning in a Developmental Cognitive Architecture. IEEE Transactions on Cognitive and Developmental Systems. 2021; 13(4): 922-933. doi: 10.1109/tcds.2020.3033963
10. Klimova B, Pikhart M. Current Research on the Impact of Foreign Language Learning Among Healthy Seniors on Their Cognitive Functions from a Positive Psychology Perspective—A Systematic Review. Frontiers in Psychology. 2020; 11. doi: 10.3389/fpsyg.2020.00765
11. Kampis D, Southgate V. Altercentric Cognition: How Others Influence Our Cognitive Processing. Trends in Cognitive Sciences. 2020; 24(11): 945-959. doi: 10.1016/j.tics.2020.09.003
12. Awad S, Debatin T, Ziegler A. Embodiment: I sat, I felt, I performed—Posture effects on mood and cognitive performance. Acta Psychologica. 2021; 218: 103353. doi: 10.1016/j.actpsy.2021.103353
13. Muller SJ. The Effects of Posture on Health Information Recall: A Randomised Trial [PhD thesis]. The University of Auckland; 2022.
14. Kim J, Kang SH, Li J, et al. Effects of a Passive Back-Support Exosuit on Postural Control and Cognitive Performance During a Fatigue-Inducing Posture Maintenance Task. Human Factors: The Journal of the Human Factors and Ergonomics

Society. 2024; 66(11): 2451-2467. doi: 10.1177/00187208231221890

15. Cervetto S, Díaz-Rivera M, Petroni A, et al. The neural blending of words and movement: event-related potential signatures of semantic and action processes during motor-language coupling. Journal of Cognitive Neuroscience. 2021; 33(8): 1413-1427. doi: 10.1162/jocn_a_01732
16. Borghi AM. A Future of Words: Language and the Challenge of Abstract Concepts. Journal of Cognition. 2020; 3(1). doi: 10.5334/joc.134
17. Macrine SL, Fugate JMB. Embodied Cognition and Its Educational Significance. Movement Matters. 2022; 13-24. doi: 10.7551/mitpress/13593.003.0006
18. Levin M. Technological Approach to Mind Everywhere: An Experimentally-Grounded Framework for Understanding Diverse Bodies and Minds. Frontiers in Systems Neuroscience. 2022; 16. doi: 10.3389/fnsys.2022.768201
19. Fei D. From ‘the mind isolated with the body’ to ‘the mind being embodied’: Contemporary approaches to the philosophy of the body. Cultures of Science. 2020; 3(3): 206-219. doi: 10.1177/2096608320960242
20. Jusslin S, Korpinen K, Lilja N, et al. Embodied learning and teaching approaches in language education: A mixed studies review. Educational Research Review. 2022; 37: 100480. doi: 10.1016/j.edurev.2022.100480
21. Marouf I, Bourouina L, & Fanit I. Teachers’ Perceptions of the Effectiveness of Using Gestures in Teaching New Vocabulary to Young English Foreign Language Learners. Novitas-ROYAL (Research on Youth and Language). 2023; 8(2): 119-135.
22. Schöllhorn WI, Rizzi N, Slapšinskaitė-Dackevičienė A, et al. Always Pay Attention to Which Model of Motor Learning You Are Using. International Journal of Environmental Research and Public Health. 2022; 19(2): 711. doi: 10.3390/ijerph19020711