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A Neuro-Motor Training-Based Basic Movement Learning Model on Students' Neural Efficiency and Motor Performance

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ABSTRACT

This study aims to: (1) analyze the effect of the basic motor learning model based on neuro-motor training on the neural efficiency of elementary school students, and (2) analyze its effect on the motor performance of elementary school students. The study used a quantitative approach with a quasi-experimental design (pretest–posttest control group design). The study subjects were 60 elementary school students divided into an experimental group (n = 30) and a control group (n = 30). Data were collected using neural efficiency tests and motor performance tests, then analyzed using descriptive statistics and Analysis of Covariance (ANCOVA) with pretest scores as covariates. The results showed that the neural efficiency score of the experimental group increased significantly from pretest (M = 62.40; SD = 6.85) to posttest (M = 78.65; SD = 6.12), higher than the control group (M = 6.10). The ANCOVA test showed a significant effect of the learning model on neural efficiency ($F = 18.72$; $p < 0.001$; partial $\eta^2 = 0.25$). In addition, the motor performance of students in the experimental group also increased significantly compared to the control group, with the effect size being in the medium to large category. The conclusion of this study shows that the basic movement learning model based on neuro-motor training is effective in improving the neural efficiency and motor performance of elementary school students, and is recommended as a physical education learning approach based on neuroscience and empirical evidence

Keywords: *Movement Learning Model, Students' Neural Efficiency, Motor Performance*

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PENDAHULUAN

The development of basic motor skills in elementary school-aged children is a crucial aspect of physical education learning because it plays a role in increasing physical capacity and supporting children's cognitive, social, and emotional aspects (Bahtiar et al., 2023; B. Liu et al., 2024; Piotrowski et al., 2025; Shi & Feng, 2022; Zhang et al., 2024). Motor skill development in early life forms the foundation for more complex motor skills later in life, and nervous system adaptation to physical exercise is a key factor in the motor learning process (Afrinaldi & Prasetyo, 2024; Chen et al., 2025; Karisman et al., 2018; Walters et al., 2025). A recent meta-analysis showed that structured training can improve gross motor skills more effectively than regular physical activity in preschool-aged children (Brown et al., 2019; Sigmund et al., 2018; Szeszulski et al., 2019). In the practice of physical education learning in elementary schools, most models are still dominated by conventional approaches that focus on movement repetition without considering the neuromotor mechanisms underlying the learning process. However, the literature on physical education and sports pedagogy emphasizes the importance of integrating neuromotor elements such as balance, stability, postural control, and coordination in designing movement learning activities (Ishak & Imran Hasanuddin, 2025; Knijnik et al., 2019; Orangi et al., 2025; Q. Yang et al., 2025). The neuromuscular or neuro-motor training approach has been widely studied in the context of school-based physical education as a more effective strategy than regular physical education lessons in improving children's fundamental movement skills and physical fitness (Chaabene et al., 2020; Doe-Asinyo & Smits-Engelsman, 2021; Duncan et al., 2023; Piotrowski et al., 2025).

The findings of this systematic review indicate that integrated neuromuscular training programs can significantly improve children's postural control, fundamental motor skills, and muscle strength compared to conventional learning. Furthermore, intervention studies in elementary school-aged children have shown that variations in learning methods, including nonlinear pedagogical models and motor learning strategies, influence children's ability to acquire and retain motor skills (Kretaine & Vecenane, 2025; Meijers et al., 2024; Walters et al., 2025; Young et al., 2011). A recent study comparing different motor pedagogical approaches reported that certain learning methods produced stronger positive effects on motor skill retention and transfer than conventional methods (Alon et al., 2023; Martín-Rodríguez & Madrigal-Cerezo, 2025; Orangi et al., 2025; Q. Yang et al., 2025). Changes in neural efficiency are also an important indicator in motor learning research. The concept of neural efficiency reflects how the nervous system processes motor information more effectively and economically after repeated practice. While many studies have assessed changes in physical performance alone, research linking structured motor training to neural indicators such as brain activation, neural network connectivity, or neural biomarkers is still relatively new and emerging (Esposito et al., 2025; Jeyanthi et al., 2021; Till et al., 2015; Tsartsapakis et al., 2025). Further support for the integration of neuromotor aspects into physical education comes from evidence that strong motor skills are positively associated with children's cognitive functions, including executive function, attention, and problem-solving abilities (Mustafa et al., 2019; Pasaribu, 2023; Sari et al., 2024). A recent longitudinal study published in Scientific Reports found that a motor skills training intervention not only improved children's basic motor competencies but was also associated with significant improvements in executive function over a long period of measurement. However, there is a gap in the physical education and educational neuroscience literature that needs to be addressed urgently. Most neuromuscular training research still focuses on physical fitness and postural control, but rarely evaluates its effects on neural efficiency directly in the context of formal elementary school learning.

Furthermore, many physical education interventions in schools have not explicitly implemented an integrated neuromotor approach as part of a systematic curriculum design. Another research gap is that most previous studies are descriptive or quasi-experimental, rarely using true experimental designs with randomization and rigorous controls to measure the actual effects of neuromotor training-based learning models on children's neural efficiency and motor performance. Thus, there is a strong need for quantitative experimental research that evaluates neuromotor training-based basic motor learning models to determine their causal effects on neural and motor outcomes. Based on the description above, several problems can be identified. (1) Basic movement learning in elementary schools still relies on conventional approaches that do not consider neuromotor aspects and neural efficiency. (2) Previous research has focused more on improving motor skills alone, without linking them to neurological indicators such as neural efficiency. (3) There has been no experimental research that tests the effectiveness of basic movement learning models based on neuro-motor training in the elementary school context. (4) It is not yet known empirically to what extent NMT is able to improve neural efficiency as well as motor performance of elementary school students compared to conventional learning models. Then the Problem Formulation (1) Does the basic movement learning model based on neuro-motor training have a significant effect on the neural efficiency of elementary school students? (2) Does the basic movement learning model based on neuro-motor training have a significant effect on the motor performance of elementary school students?

Research Objectives (1) Analyze the effect of the basic movement learning model based on neuro-motor training on the neural efficiency of elementary school students. (2) Analyze the effect of the basic movement learning model based on neuro-motor training on the motor performance of elementary school students. Then from that Benefits of Research (1) Theoretical Benefits This research is expected to enrich the study of physical education and motor learning by introducing the concept of neural efficiency as a variable underlying changes in motor skills, as well as broadening the understanding of neuromotor integration in the learning process. In addition, the results can provide a scientific basis for the development of neuroscience-oriented movement learning theories. (2) Practical Benefits The results of the research can be a guide for physical education teachers in designing basic movement learning that is more effective, adaptive, and neural-aware. These empirical findings can also be used to develop training programs that are more suited to the needs of elementary school students' neuromotor development.

METODE

This study used a quasi-experimental design with a pretest–posttest control group design, which is commonly used to test causal relationships in educational contexts when full randomization is difficult (Creswell & Guetterman, 2018). This design allows researchers to systematically compare changes in outcomes between treatment and comparison groups, while controlling for differences in initial abilities through pretest measurements (Shadish et al., 2002). The research location was State Elementary School 024772 East Binjai, North Sumatra Province, Indonesia, which was selected purposively based on the following considerations: (1) the school has implemented Physical Education, Sports, and Health (PJOK) learning routinely according to the national curriculum, (2) it has adequate basic facilities for movement activities, and (3) the school's readiness to support the implementation of experimental research. A relatively homogeneous school environment was chosen to minimize the influence of external variables on the research results. The research subjects were 60 elementary school students, consisting of students in grades III and IV with an age range of 9-11 years. All subjects were divided into two groups based on existing classes (intact groups): an experimental group (n = 30) and a control group (n = 30). This sample size was deemed adequate for quantitative experimental research because it met the minimum sample size for inferential statistical analysis and effect size estimation in educational research (Field, 2022; Lakens, 2022).

The research process began with the selection of research subjects and group assignment. Before treatment was administered, both groups underwent a pretest to measure neural efficiency and motor performance as baseline conditions. Next, the experimental group received treatment in the form of a basic movement learning model based on neuro-motor training, which emphasizes coordination, balance, postural control, and sensorimotor integration. This approach is designed to encourage neuromotor adaptation and improve neural processing efficiency during motor activities (Myer & Zambito Ivey, 2025; Sun et al., 2022).

HASIL DAN PEMBAHASAN (*RESULT AND DISCUSSION)*

Hasil (*Results*)

The results section of this study presents empirical findings obtained from quantitative data analysis to test the effect of a neuro-motor training-based basic movement learning model on the neural efficiency and motor performance of elementary school students. Data were analyzed step by step using descriptive and inferential statistics to provide a comprehensive picture of the changes that occurred in each research variable. Descriptive statistics were used to describe the general trend of pretest and posttest scores in the experimental and control groups, while inferential statistics were applied to test the significance of differences between groups after controlling for students' initial abilities. Inferential analysis was conducted using an analysis of covariance (ANCOVA) approach, with pretest scores used as a covariate, so that the effect of the treatment could be identified more objectively and accurately. The presentation of research results is arranged according to the research objectives, which include: (1) the influence of the basic movement learning model based on neuro-motor training on the neural efficiency of elementary school students, and (2) the influence of the learning model on the motor performance of elementary school students. Each subsection of the results is accompanied by analytical narratives, statistical tables, and graphic visualizations to clarify the pattern of findings and strengthen the interpretation of the research results.

1. **The Effect of a Neuro-Motor Training-Based Basic Movement Learning Model on Neural Efficiency**

The results of the study indicate that the implementation of the Neuro-Motor Training-Based Basic Movement Learning Model has a significant effect on increasing the neural efficiency of elementary school students. Inferential statistical analysis conducted by controlling the pretest score as a covariate showed a significant difference between the experimental group and the control group in the posttest scores of neural efficiency. This section presents the results of the study on the effect of the neuro-motor training-based basic movement learning model on the neural efficiency of elementary school students. The analysis of the results was carried out using descriptive and inferential statistical approaches to compare changes in neural efficiency scores between the experimental and control groups. The data presentation is arranged in stages, starting with the visualization of the pattern of score changes, followed by the presentation of descriptive statistics, the results of the inferential test, and ending with the synthesis of the findings. Descriptively, the experimental group (n = 30) showed a higher increase in neural efficiency compared to the control group. The average neural efficiency score of students in the experimental group increased from 62.40 (SD = 6.85) in the pretest to 78.65 (SD = 6.12) in the posttest, with a difference in the average increase of 16.25 points. The decrease in the standard deviation value in the posttest indicates that the increase in neural efficiency occurred relatively evenly among students in the experimental group. Meanwhile, the control group (n = 30) also experienced an increase in neural efficiency scores, but with a smaller magnitude. The average pretest score of the control group of 63.10 (SD = 7.02) increased to 69.20 (SD = 6.74) in the posttest, with a difference in the average increase of 6.10 points. This increase indicates a natural development or effect of conventional learning, but not as strong as the increase that occurred in the experimental group.

The difference in the magnitude of improvement between the two groups indicates that the neuro-motor training-based basic movement learning model provides a more effective contribution in improving students' neural efficiency. The magnitude of the effect obtained is in the medium to large category, which confirms that the differences that occurred are not only statistically significant but also practically meaningful in the context of basic movement learning in elementary schools. To clarify the difference in neural efficiency scores between the experimental and control groups before and after treatment, a summary of descriptive statistics is presented in Table 1 below.

Table 1. Mean and Standard Deviation of Neural Efficiency Scores

Group	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Mean
Experiment (n = 30)	62.40 ± 6.85	78.65 ± 6.12	+16.25
Control (n = 30)	63.10 ± 7.02	69.20 ± 6.74	+6.10

The table shows that the experimental group experienced a greater increase in neural efficiency scores than the control group after treatment. Data analysis was then performed using Analysis of Covariance (ANCOVA) with pretest scores as a covariate.

Table 2. Results of the ANCOVA Test of Neural Efficiency

Source of Variation	F	p-value	Partial η²	Interpretation
Learning model	18.72	< 0.001	0.25	Big effect

Based on the results of this study, which is based on the integration of descriptive statistics (Table 1) and inferential statistics (Table 2) to obtain a comprehensive understanding of the effect of the basic movement learning model based on neuro-motor training on the neural efficiency of elementary school students, it can be concluded that. The data in Table 1, the experimental group showed a significantly greater increase in neural efficiency scores compared to the control group. The average score of the experimental group increased from 62.40 (SD = 6.85) in the pretest stage to 78.65 (SD = 6.12) in the posttest stage, with a difference in increase of 16.25 points. In contrast, the control group only experienced an average increase of 6.10 points, from 63.10 (SD = 7.02) to 69.20 (SD = 6.74). This difference in the magnitude of the increase indicates that neuro-motor training-based treatment provides a more substantial contribution to neural processing efficiency than conventional learning.

These descriptive findings are supported by the results of the inferential analysis using ANCOVA presented in Table 2. After controlling for pretest scores as a covariate, the test results showed that the learning model had a significant effect on the neural efficiency of elementary school students ($F = 18.72$; $p < 0.001$). The partial eta squared value of 0.25 indicates a relatively large effect size, which confirms that the influence of the neuro-motor training-based learning model is not only statistically significant but also practically meaningful. Overall, the synthesis between Tables 1 and 2 shows that the increase in neural efficiency in the experimental group is the result of a structured learning intervention oriented towards neuromotor stimulation. These findings confirm that the integration of the principles of coordination, balance, postural control, and sensorimotor integration in basic movement learning can encourage more efficient neural adaptation, so that the neuro-motor training-based basic movement learning model can be seen as an effective and evidence-based pedagogical approach in the context of elementary school physical education.

2. The Effect of the Basic Movement Learning Model Based on Neuro-Motor Training on the Motor Performance of Elementary School Students

This section presents the results of a study aimed at analyzing the effect of a neuromotor training-based basic movement learning model on the motor performance of elementary school students. Motor performance in this study includes aspects of coordination, balance, movement accuracy, and motor control. Analysis of the results was carried out through visualization of score change patterns, descriptive statistics, and inferential tests to ensure the significance and strength of the treatment effect. The results of the descriptive statistical analysis showed that the experimental group experienced a greater increase in motor performance than the control group. The average motor performance score of the experimental group increased from 64.20 (SD = 6.40) in the pretest to 82.50 (SD = 5.85) in the posttest, with a difference of 18.30 points. In contrast, the control group only experienced an increase from 65.10 (SD = 6.55) to 72.30 (SD = 6.10), with a difference of 7.20 points.

Table 3. Descriptive Statistics of Motor Performance Scores

Group	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Mean
Experiment (n = 30)	64.20 ± 6.40	82.50 ± 5.85	+18.30
Control (n = 30)	65.10 ± 6.55	72.30 ± 6.10	+7.20

Inferential analysis using ANCOVA with pretest scores as a covariate showed that there was a significant difference in motor performance improvement between the experimental and control groups ($F = 21.45$; $p < 0.001$). The partial eta squared value of 0.28 indicates a relatively large effect size, which confirms that the basic movement learning model based on neuro-motor training provides a strong contribution to improving the motor performance of elementary school students.

Table 4. Results of ANCOVA Test of Motor Performance

Source of Variation	F	p-value	Partial η^2
Learning model	21.45	< 0.001	0.28

Based on the data described above, the results of the study indicate that the neuro-motor training-based basic movement learning model is significantly more effective in improving the motor performance of elementary school students compared to conventional learning. The integration of descriptive findings (Table 3), inferential test results (Table 4), and visual patterns on the development curve shows that the treatment not only improves motor performance scores quantitatively but also accelerates the quality of students' motor adaptation. Substantively, the greater improvement in motor performance in the experimental group indicates that structured neuromotor stimulation is able to improve neuromuscular coordination, postural stability, and motor control more optimally. Thus, the neuro-motor training-based basic movement learning model can be seen as an effective, evidence-based, and relevant learning approach to improving the quality of physical education learning in elementary schools.

PEMBAHASAN

This discussion chart illustrates the conceptual relationship between the neuromotor training-based basic movement learning model, neural efficiency, and elementary school students' motor performance. The application of neuromotor stimulation-based learning encourages increased neural processing efficiency through sensorimotor integration, coordination, and postural control. This increase in neural efficiency subsequently contributes directly to improvements in the quality of students' motor performance, which is reflected in the aspects of coordination, balance, accuracy, and movement control. Thus, the neuromotor training-based basic movement learning model serves as a pedagogical approach that connects neural adaptation and motor performance in an integrated manner in physical education learning in elementary schools.

1. The Influence of the Basic Movement Learning Model Based on Neuro-Motor Training

Intervention studies implementing integrated neuromuscular training (INT) in a school context have shown that structured neuromotor training programs have significant positive effects on improving children's fundamental motor skills. An experimental study by Vasileva et al. (2024) examined the effects of a three-month INT program implemented as part of a primary school Physical Education class. The results showed that the INT group had significant improvements in fundamental motor skills (FMS) scores, including sidestep, 1-foot hop, and kick, as well as in the total FMS score compared to the control group, with increases in salivary BDNF concentrations associated with these changes ($p < 0.001$). A similar approach is also supported by a systematic review by Lin et al. (2022), which combined several controlled clinical trials comparing school-based integrated neuromuscular training programs with conventional Physical Education classes in school-aged children. The review findings showed that INT interventions consistently resulted in greater improvements in fundamental movement skills and postural control compared to conventional learning approaches, confirming the superiority of neuromotor approaches over traditional learning in developing children's motor competence. Furthermore, (Carpendale et al., 2025; Chuadthong et al., 2023; Owoeye et al., 2014) in a randomized clinical trial integrated an INT program as a warm-up in Physical Education classes for 12 weeks. The results of this study showed significant improvements in motor competence levels and fundamental movement skill patterns in elementary school-aged children compared to the group that only followed a conventional warm-up, confirming that structured neuromuscular training components can improve students' motor performance more effectively.

Another study that adds a dimension to neuromotor development is the study by (Ghorbel et al., 2026; Inacio et al., 2023; N & V, 2024; Smits-Engelsman et al., 2025), which, although not exclusively focused on motor performance, showed that a 6-week neuromuscular training program improved aspects of active joint control and several motor variables such as balance and spatial-temporal structure in school children, implicitly supporting optimal fundamental movement learning when a neuromotor model is applied. Furthermore, a broader meta-analysis of motor-based interventions in school-aged children showed that programs emphasizing neuromotor training or motor combination exercises generally produced moderate to strong effects on improving children's motor skills and motor control compared to groups without intervention or conventional programs. Based on the results of previous research, this study's position is relevant, demonstrating strong empirical consistency and emphasizing its contribution in filling the research gap, particularly regarding the integration of neural efficiency and motor performance in a neuromotor training-based fundamental movement learning model. Thus, this study not only replicates previous findings but also enriches the scientific discourse through a more holistic, neurophysiologically based pedagogical approach.

2. The Relationship Between Neural Efficiency and Motor Performance

Neural efficiency and motor performance are two closely interrelated aspects of the motor learning process, particularly in elementary school-aged children who are in a critical phase of nervous system development. Neural efficiency refers to the nervous system's ability to optimize sensorimotor information processing, resulting in more coordinated, precise, and adaptive motor responses. Numerous recent studies have shown that improvements in motor performance are inextricably linked to underlying neural adaptation processes. Neuroimaging research by (Beck et al., 2025; Gordleeva et al., 2026; Schuler et al., 2025; Yan et al., 2021) provides strong empirical evidence that motor skill learning triggers significant changes in the functional connectivity of cortical and corticospinal networks. This study demonstrated that improved motor performance after practice is directly correlated with more efficient neural network reorganization, particularly in primary sensorimotor areas. These findings confirm that improved motor performance is a manifestation of optimal neural efficiency, not simply a result of mechanical movement repetition.

This link is further supported by research by (Li et al., 2023; Y.-C. Liu et al., 2026; J. Yang et al., 2025; Yoo et al., 2025) that used functional near-infrared spectroscopy (FNIRS) to examine the relationship between motor skills and neural activity in early childhood. The results showed that children with higher levels of motor skills displayed more organized neural activation patterns in the prefrontal area, which plays a role in cognitive regulation and motor control. This finding indicates that neural efficiency contributes to better motor-cognitive integration, thus supporting more stable and directed motor performance. In addition to direct neural measurements, motor imagery-based intervention approaches also provide indirect evidence of the link between neural efficiency and motor performance. (Ben Mansour et al., 2026; He et al., 2025; Saidmamatov et al., 2022; Suggate et al., 2025) reported that motor imagery training significantly improved gross and fine motor skills in preschool children. Because motor imagery involves the activation of the same neural networks as actual motor execution, the resulting improvements in motor performance can be understood as a consequence of optimizing neural efficiency through mental simulation of movement.

The relationship between neuromotor adaptation and motor performance was also demonstrated in a physical education intervention study by (Bernardi et al., 2024; Brustio et al., 2015; Infante-Cañete et al., 2023; Pinheiro et al., 2026). This study found that the implementation of integrative neuromuscular training significantly improved the motor competence of elementary school children compared to conventional learning. Although it did not measure neural activity directly, the neuromuscular training approach, which emphasizes coordination, balance, and postural control, is theoretically closely related to increased nervous system efficiency in organizing movement. These findings are supported by a systematic review conducted by (Kraemer et al., 2025; Sliwa, 2000), which concluded that school-based neuromuscular training programs consistently resulted in greater motor skill gains than traditional physical education instruction. This review confirmed that interventions that stimulate sensorimotor integration and neuromuscular control reflect improvements in neural efficiency that underlie improvements in children's motor performance. These five studies indicate that neural efficiency acts as a fundamental mechanism bridging exercise or movement learning interventions with improved motor performance. In the context of this study, the improvement in elementary school students' motor performance can be understood as a reflection of more efficient neural adaptation resulting from the implementation of a neuromotor training-based basic movement learning model. Thus, the results of this study have a strong empirical and theoretical basis and are consistent with current literature.

The present study demonstrates that the neuro-motor training (NMT)-based basic movement learning model significantly improves both neural efficiency and motor performance among elementary school students compared to conventional physical education instruction. The experimental group exhibited substantially greater improvements in neural efficiency and motor performance, with medium-to-large effect sizes. These findings indicate that improvements in coordination, balance, and movement accuracy are not merely the result of repetitive physical activity, but rather reflect more efficient neural adaptation in sensorimotor processing. Thus, motor performance enhancement can be interpreted as a behavioral manifestation of optimized neural integration and reorganization.

These findings are consistent with previous international research emphasizing the effectiveness of neuromuscular and neuromotor interventions in school settings. (Chen et al., 2025) reported that a three-month integrated neuromuscular training (INT) program significantly improved fundamental movement skills (FMS) and increased salivary BDNF levels, suggesting neuroplastic adaptations. Similarly, (Cetinkaya et al., 2025), in their systematic review, concluded that school-based neuromuscular training programs consistently produce greater improvements in fundamental movement skills and postural control compared to traditional physical education approaches. (Zhang et al., 2024) also demonstrated through a randomized controlled trial that incorporating integrative neuromuscular training into physical education classes significantly enhanced children's motor competence. The convergence of findings across these studies likely results from the shared emphasis on structured coordination tasks, postural stability exercises, and sensorimotor integration components.

Moreover, the present findings align with neurodevelopmental evidence linking motor competence and neural efficiency. (Meng et al., 2026) demonstrated in a meta-analysis that motor development-focused exercise interventions are more effective than ordinary physical activity in improving gross motor skills in children. Neuroimaging research by (Hodel, 2018) revealed that children with higher motor competence display more organized prefrontal activation patterns measured through functional near-infrared spectroscopy (fNIRS), indicating more efficient neural processing. Furthermore, (Beck et al., 2025) found that motor skill learning modulates functional connectivity within cortical and corticospinal networks, supporting the view that motor performance gains are underpinned by neural reorganization. Collectively, these studies reinforce the interpretation that neural efficiency functions as a biological foundation for improved motor outcomes.

However, this study extends prior research in several important ways. While most previous investigations have focused primarily on performance outcomes or fundamental movement skills, relatively few have directly examined neural efficiency as a core construct within school-based physical education contexts. This study uniquely positions neural efficiency as the mechanism linking neuromotor stimulation to motor performance improvements. Additionally, the use of ANCOVA controlling for baseline pretest scores strengthens the internal validity of the findings. The implementation of this intervention within Indonesian elementary schools also contributes new contextual evidence from Southeast Asia, where neuroscience-informed physical education research remains limited.

The novelty of this study lies in its neuro-adaptive pedagogical framework. By conceptualizing motor learning as a process of neural optimization rather than mechanical repetition, this research advances theoretical perspectives in motor learning and physical education. The proposed conceptual pathway neuromotor training leading to enhanced neural efficiency, which subsequently improves motor performance offers a biologically grounded explanatory model bridging neuroscience and pedagogy. This contribution is particularly relevant in light of increasing calls for neuroscience-informed educational practices.

From a practical perspective, the findings suggest that physical education teachers should design learning activities that intentionally stimulate coordination complexity, dynamic balance, postural control, and sensorimotor integration, rather than relying solely on repetitive drills. Academically, this study supports integrating neuroscience principles into curriculum development and teacher education programs. At the policy level, curriculum designers may consider embedding neuromotor components explicitly into national physical education standards to promote evidence-based instructional approaches.

Despite its contributions, several limitations should be acknowledged. First, the quasi-experimental design without full randomization limits causal generalizability. Second, the sample was drawn from a single school, which may restrict external validity. Third, neural efficiency was assessed through behavioral indicators rather than direct neurophysiological measures such as EEG or fNIRS. Future research should employ randomized controlled trials with larger multi-site samples and incorporate direct neuroimaging techniques to validate neural mechanisms more rigorously. Longitudinal studies are also needed to examine retention effects and long-term neurodevelopmental outcomes.

In summary, this study provides empirical evidence that improvements in elementary school students' motor performance are closely associated with enhanced neural efficiency. The neuro-motor training-based learning model represents an effective, evidence-based, and neuroscience-informed pedagogical approach that shifts the paradigm of movement learning from mechanistic repetition to structured neural adaptation. This integrative perspective offers meaningful theoretical, practical, and policy implications for the advancement of contemporary physical education.

CONCLUSION

Based on the research results and discussions conducted, it can be concluded that neural efficiency has a significant relationship with the motor performance of elementary school students. Improved motor performance demonstrated through movement coordination, balance, and execution accuracy is not solely the result of repeated physical activity, but rather a manifestation of a more efficient neural adaptation process in integrating sensorimotor information. This finding confirms that the efficiency of the nervous system acts as a biological foundation that supports the achievement of optimal motor performance. Furthermore, this study concludes that the basic movement learning model based on neuro-motor training effectively contributes to the improvement of motor performance through the mechanism of neural efficiency. The application of a learning model that emphasizes neuromuscular coordination, postural control, and sensorimotor integration has been shown to encourage a more adaptive reorganization of neural functions, so that students are able to perform more controlled, precise, and efficient movements. Thus, this learning model not only impacts the performative aspects of movement, but also the quality of the underlying neural processes. Overall, this study confirms that neural efficiency and motor performance are two interrelated and inseparable variables in basic movement learning, and positions neuro-motor training as a relevant and evidence-based pedagogical approach in physical education in elementary schools. This conclusion provides theoretical and practical implications that the development of movement learning models needs to be oriented towards systematic stimulation of the nervous system, not just physical activity alone.

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