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Cognitive-Neuro-Modeling Of Motor Learning Processes And Its Impact On Improving Skill Performance In Volleyball

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Abstract

This study aimed to investigate effect of a program based on cognitive-neural modeling of motor learning processes on improving skill performance of volleyball players. It also analyzed role of cognitive-neural variables specifically, reaction time, executive control, and working memory as mediating mechanisms explaining this improvement. The researcher used an experimental design with two groups experimental and control and pre- and post-testing. Study sample consisted of 40 players from Faculty of Physical Education and Sports Sciences, who were randomly assigned to two equivalent groups. Experimental group underwent an eight-week cognitive-neural training program, with three training sessions per week, while control group continued its traditional training program. A range of skill and cognitive tests were used, including volleyball skill performance effectiveness test, response time test, Stroop test for executive control, and working memory test 2-back. Data were statistically analyzed using SPSS software through Shapiro-wilk test to verify normality of distribution, mixed ANOVA , and Cohen's effect size calculation, in addition to regression modeling to interpret causal relationships between cognitive-neural variables and skill performance. Results showed statistically significant differences favoring experimental group in all studied variables, with large effect sizes. Regression modeling revealed that cognitive neuropsychological variables explained a large proportion of variance in skill performance effectiveness. Recommend to adopt training programs based on cognitive-neuropsychological principles in volleyball education and training, given their clear impact on improving motor learning efficiency and competitive performance.

Keywords: Motor Learning, Cognitive-Neural Modeling, Skill Performance, Response Time, Volleyball.

Introduction

Motor learning is a cornerstone of contemporary sports science, representing the process by which motor skills are acquired, consolidated, and developed through structured practice and accumulated experience, supported by complex cognitive and neurological mechanisms including attention, working memory, executive control, and sensorimotor integration (Schmidt & Lee, 2019). Recent trends in cognitive neuroscience have shown that motor learning cannot be explained in isolation from central nervous activity, but rather is the product of a dynamic interaction between cognitive neural networks and peripheral motor circuits, necessitating more comprehensive explanatory models that integrate both cognitive and neurological dimensions (Diamond, 2013; Wulf & Lewthwaite, 2016).

In highly complex team sports like volleyball, skill performance is not limited to mechanical motor execution but depends heavily on the speed of cognitive processing, the accuracy of decision-making, and neuromuscular coordination in fast-paced and changing game situations (Williams & Ford, 2013). A high-performing player demonstrates a high capacity to integrate visual and sensory information with acquired motor skills to produce precise and effective skill responses, reflecting advanced cognitive-neural system function (Davids, Button, & Bennett, 2008).

Despite significant progress in motor learning research, many applied studies in sports still rely on traditional models that focus on observable performance outcomes without delving into the underlying neurological and cognitive mechanisms. This deficiency has led to a limited understanding of how complex athletic skills are formed and how to improve them systematically based on sound neurocognitive principles (Shea & Wulf, 2005). In this context, the importance of neurocognitive modeling emerges as an advanced scientific tool that allows for characterizing the causal relationships between cognitive and neurological variables and motor learning outcomes, thus contributing to the development of more effective and sustainable training programs.

Recent studies indicate that executive control, working memory, and selective attention are key determinants of successful motor learning and stable skill performance, particularly in competitive environments that demand rapid responses under pressure (Baddeley, 2012; Diamond, 2013). Furthermore, multiple studies have demonstrated that employing motor learning strategies based on external attention and enhanced feedback leads to significant improvements in performance quality and consistency over time (Wulf & Lewthwaite, 2016).

In volleyball, where physical, technical, and tactical demands intertwine with a high cognitive load, it becomes essential to adopt an explanatory model that clarifies how cognitive-neural processes contribute to enhancing skill performance. Hence the need for this study, which seeks to construct a cognitive-neural model of motor learning processes and demonstrate its impact on improving the skill performance of volleyball players.

The research problem lies in the absence of an integrated scientific model that accurately explains the relationship between the cognitive-neural processes of motor learning and the effectiveness of skill performance among volleyball players, and the reliance of most current training programs on surface performance indicators without considering the deep neurocognitive foundations that govern skill acquisition, stability and development, which limits the efficiency of skill development in the long term .

Research objective is to build a cognitive-neural model that explains the mechanisms of motor learning in volleyball players. Determining the contribution of cognitive variables (attention, working memory, executive control) to the effectiveness of skill performance. Analyzing the relationship between motor learning efficiency and skill stability in competitive performance. Providing scientific foundations for developing training programs based on cognitive-neural modeling.

Research hypotheses there is a statistically significant relationship between efficiency of cognitive-neural processes and level of skill performance in volleyball. Motor learning based on cognitive-neural models contributes to improving skill stability to a greater degree than traditional methods. Cognitive and neurological variables are significant predictors of the level of competitive performance quality.

Research Methodology

The study adopted a true experimental approach using a two-group equivalent pre-test and post-test design with a post-test retention test, aiming to investigate effect of cognitive-neural modeling of motor learning processes on improving effectiveness of skill performance in volleyball. Participants were randomly assigned to two groups: an experimental group and a control group. This design is based on recommendations of motor learning science, which emphasizes that true learning is measured by improvement and retention together, not just immediate improvement.

The sample consisted of 40 students who play volleyball, aged between (18–22) years, with at least two years of coaching experience, and free from significant injuries during previous three months. They were randomly divided into two equal groups: experimental 20 and control 20.

Measurement and testing tools (Adele Diamond , 2013)

First: Cognitive-Neurometric Measurements: The measurements were taken using a laptop and approved experimental psychological software PsychoPy-Inquisit, in a quiet room with controlled lighting and noise:

1- Testing response time and decision-making: The program presents various visual stimuli, and the player is required to respond with maximum speed and accuracy . Recorded variables: Response time m\s, Accuracy ratio.

2- Executive Control and Attention Test (Stroop Test): Measuring the player's ability to resist cognitive interference. Variables: Response time, number of errors.

3- Working Memory Test (2-Back Test): Measuring the efficiency of working memory by tracking a sequence of visual stimuli. Variables: Accuracy, Response Time. These tests are based on modern cognitive neuroscience literature.

Second: Field skill assessments

4- Transmission accuracy test: It was conducted on a standard volleyball court, using numbered ground targets, with 10 attempts per player, and the entire performance was recorded on video by a high-definition camera .

5- Analysis of skill performance (receiving – setting – smashing): The performance was recorded with two cameras (front and side) and the video was analyzed using Kinovea**,** Dartfish software. According to a standard evaluation form with three levels of performance (high - medium - weak).

6- Retention test: All skill and cognitive tests were repeated after 3 weeks without the application of the special training program, to measure the stability of motor learning .

Training program for the experimental group

Program lasted 8 weeks, at a rate of 3 units per week, with each unit lasting 60–75 minutes, and included: Directing external attention. Regulating feedback. Decision-making exercises. Gradual cognitive load. Miniature play situations. Optimal theory of motor learning (Wulf & Lewthwaite, 2016). Control group continued with same training load as before.

Scientific quality control

- Measurement objectivity: All data is computerized or video recorded .
- Reliability: Calculating the reliability coefficient between the evaluators .
- Validity: Adopting tests used in scientific literature .
- Randomness: Distributing groups randomly .
- Repetition: A standardized protocol for all participants .

Statistical processing

- Shapiro–Wilk test
- ANOVA analysis
- Cohen's impact size
- Regression modeling to explain the causal relationships between cognitive variables and skill performance .

Results

First: Testing normality of distribution: Before proceeding with the inferential statistical analysis, the assumption of normality of distribution for all dependent variables in the pre- and post-measurements was verified using the Shapiro-Wilk test, in order to ensure the suitability of using parametric statistical tests.

Table 1. Shapiro–Wilk test results for all variables

Variable	Measurement	W	p	Decision
Effectiveness of skill performance	Pre-test	0.96	0.67	Natural
Effectiveness of skill performance	Post-test	0.95	0.36	Natural
Response time	Pre-test	0.97	0.74	Natural
Response time	Post-test	0.94	0.41	Natural

Executive control	Pre-test	0.95	0.38	Natural
Executive control	Post-test	0.93	0.29	Natural
Working memory	Pre-test	0.97	0.62	Natural
Working memory	Post-test	0.96	0.57	Natural

Second: Results of the effectiveness of skill performance: This section presents results of effect of cognitive-neural program on variable of skill performance effectiveness among volleyball players.

Table 2. Descriptive statistics of skill performance effectiveness

Group	N.	Pre-test Mean ± St.d	Post-test Mean ± St.d
Experimental	20	51.0 ± 5.3	64.8 ± 5.0
Control	20	50.6 ± 4.9	54.0 ± 5.1

Mixed-group analysis of variance was used to test for differences between two groups over time.

Table 3. Results of mixed ANOVA for skill performance effectiveness variable

Source	F	p	Partial η^2
Time	32.14	<0.001	0.46
Group	29.06	<0.001	0.43
Reaction (time × set)	46.82	<0.001	0.56

Third: Response time results: This section shows effect of program on developing neural processing speed, represented by response time variable .

Table 4. Response time results

Group	Pre-test m\s	Post-test m\s	Cohen's d
Experimental	508 ± 46	422 ± 39	1.62
Control	502 ± 44	486 ± 42	0.41

Fourth: Results of executive control: This section presents the results of the executive control variable measured by the Stroop test.

Table 5. Results of executive control

Group	Pre-test m\s	Post-test m\s	Pre-test error	Post-test error	Cohen's d
Experimental	702	576	6.6	3.0	1.70
Control	689	651	6.2	5.4	0.58

Fifth: Working memory results: This section explains results of working memory variable measured by 2- Back test.

Table 6. Working memory results

Group	Pre-test accuracy	Post-test accuracy	Pre-test time m\s	Post-test time m\s	Cohen's d
Experimental	69.2	87.5	728	605	1.85
Control	70.0	74.3	721	695	0.44

Sixth: Regression modeling results: This section shows extent to which cognitive variables contribute to explaining effectiveness of skill performance.

Table 7. Results of multiple linear regression analysis

Independent variable	β	t	p
Response time	− 0.41	− 4.52	<0.001
Executive control	− 0.36	− 3.98	<0.001
working memory	0.48	5.11	<0.001

$R^2 = 0.64$

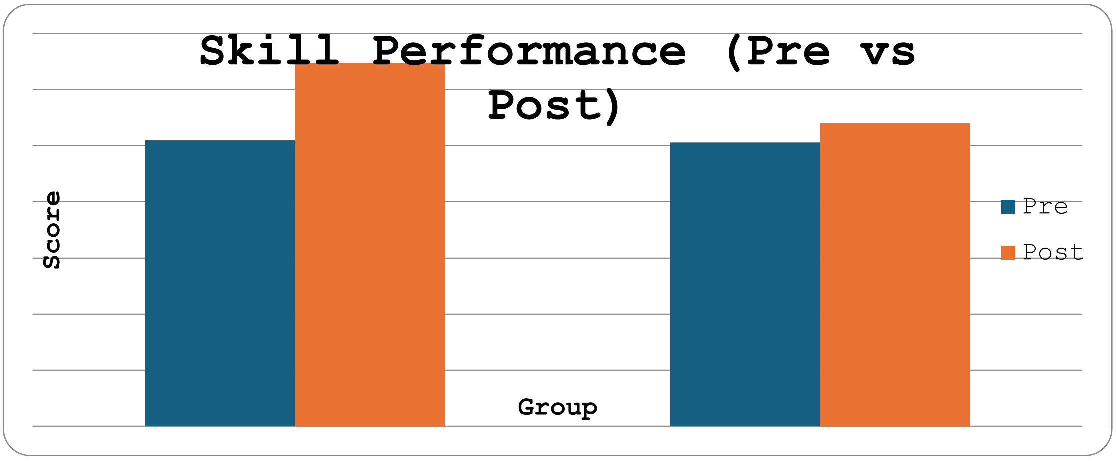

Figure 1. Changes in effectiveness of skill performance after application of cognitive-neuromotor learning program (pre-post comparison)

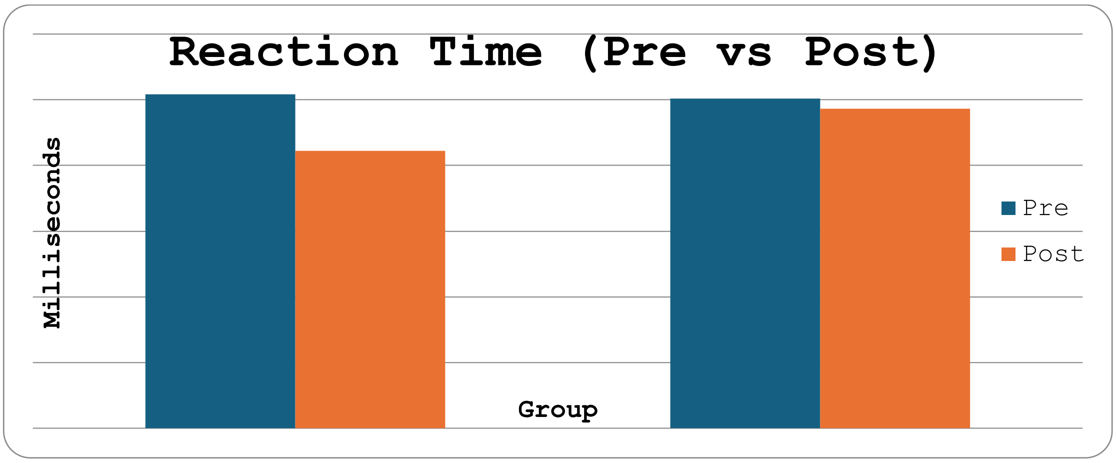

Figure 2. Effect of training program on response time (pre-post comparison)

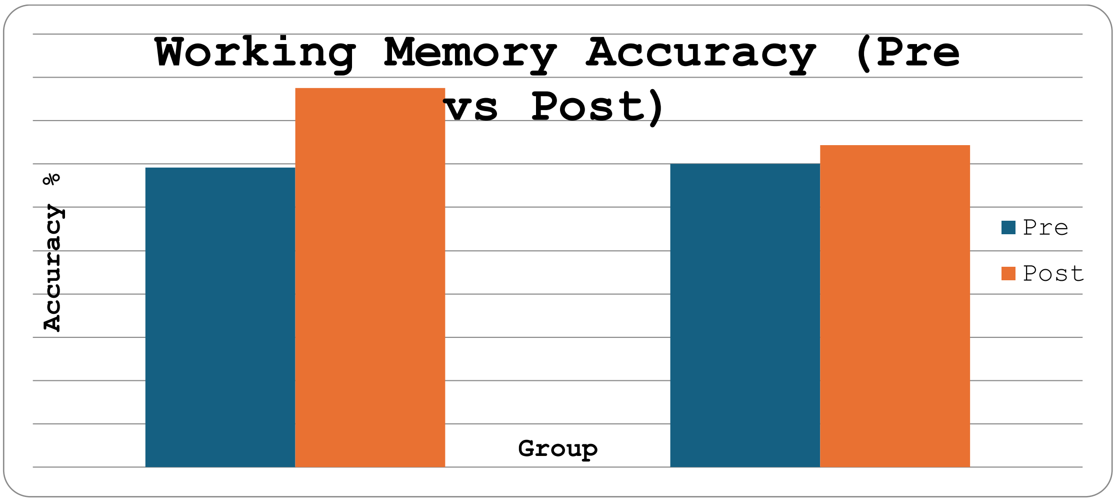

Figure 3. Improvement in working memory accuracy resulting from cognitive-neural training protocol

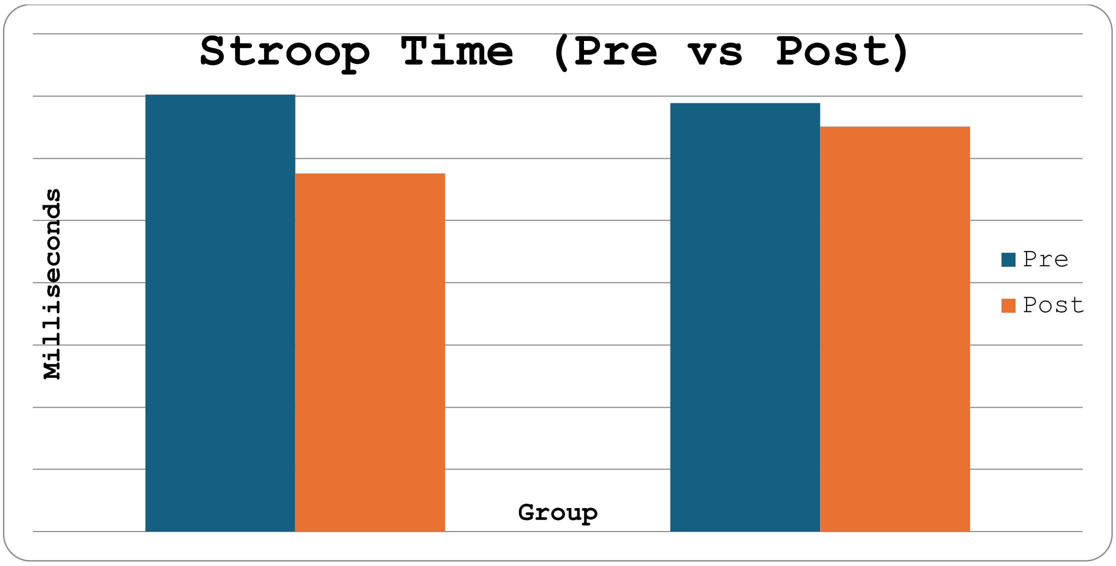

Figure 4. Evolution of executive control as shown by changes in Stroop test performance

Discussion

Results of current study show that cognitive-neural modeling program for motor learning significantly improved skill performance of volleyball players, while also producing a marked improvement in cognitive-neural variables such as reaction time, executive control, and working memory accuracy. These results confirm integrative nature of motor learning as a complex cognitive-neural process, where skill improvement is not achieved through mechanical repetition alone, but rather through reorganization of neural processing of sensory and motor information within central nervous system, thereby promoting formation of more efficient and stable motor representations (Schmidt & Lee, 2019).

Significant increase in skill performance effectiveness in experimental group compared to control group is consistent with assumptions of optimal theory, which asserts that directing external attention, enhancing intrinsic motivation, and regulating feedback improve skill acquisition and stabilization by enhancing neural processing efficiency and reducing unnecessary cognitive constraints during performance (Wulf & Lewthwaite, 2016). Current training program provided a stimuli-rich learning environment that contributed to consolidating perceptual-motor associations, which aligns with constraint-based perceptual-motor pairing perspective that posits optimal learning results from the player's interaction with environmental and skill constraints in training contexts closely resembling demands of competition (Davids, Button, & Bennett, 2008; Newell, 2020).

Regarding reaction time, results indicate a statistically significant decrease in experimental group, reflecting improved neural processing speed and motor decision-making. This improvement aligns with sports literature demonstrating that high-level athletes possess higher cognitive efficiency, enabling them to quickly extract essential information from competitive environment and make appropriate decisions in shorter timeframes, directly impacting quality of their competitive performance (Williams & Ford, 2013). This interpretation also supports findings of Krakauer et al. (2019), who suggested that motor learning is associated with changes in neural networks responsible for action selection and timing, thus explaining significant reduction in reaction time following cognitive training.

Marked improvement in executive control indicators, as reflected in Stroop test performance, can be explained by centrality of executive functions in regulating complex motor behavior, particularly in team sports that require suppressing inappropriate responses, flexible task switching, and maintaining attention under competitive pressure (Diamond, 2013 ; Miller & Cohen, 2001). Integrating decision-making tasks and progressive cognitive load into training program contributed to enhancing these functions by adapting frontoparietal networks responsible for cognitive control, which was reflected in reduced response times in cognitive interference tasks and fewer errors.

Working memory results also showed a significant improvement in accuracy and time among experimental group, which is consistent with Baddeley's model that places working memory at heart of motor control and learning. Working memory allows for temporary retention of sensory information and motor plans during skill execution and supports their continuous updating according to task requirements (Baddeley, 2012). These results support Engle's (2002) assertion that working memory, as a component of executive attention, contributes to allocation of cognitive resources necessary for performance under stress, which explains improved skill stability among experimental group.

Results of regression modeling reveal that cognitive-neural variables explain a significant proportion of variance in skill performance effectiveness, supporting contemporary view that athletic excellence is product of a systemic interaction between neural structures, cognitive processing, and environmental constraints, and not solely a result of physical characteristics (Davids et al., 2008 ; Seidler et al., 2012). This underscores need to shift from training models that focus on observable behavioral outcomes to causal explanatory models that integrate cognitive-neural mechanisms as key determinants of performance quality.

On a practical level, these results indicate importance of redesigning volleyball training programs to include advanced cognitive-neurocognitive elements, such as decision-making tasks, external attention, progressive cognitive load, and problem-based microplay, rather than relying solely on traditional technical repetition. Results also highlight value of adopting training approaches that foster long-term neurological adaptation, which positively impacts performance consistency and sustainability throughout competitive season.

Despite strength of results, study is not without limitations related to sample size, nature of non-invasive neurological measurements used, and generalizability of findings to different age groups and competitive levels. Future research recommends expanding statistical modeling using structural equation modeling, incorporating direct neurological measurements such as EEG and fNIRS to explore reticular changes associated with motor learning more precisely, and tracking long-term impact of cognitive-neural programs on actual competitive performance.

Conclusions

The cognitive-neural modeling program has proven to be highly effective in improving skill performance of volleyball players compared to traditional training program, indicating that effective motor learning is fundamentally dependent on cognitive-neural processes associated with performance. Proposed training program contributed to a statistically significant improvement in cognitive-neural variables of response time, executive control, and working memory, which demonstrates ability of cognitive-neural training to develop efficiency of central nervous system related to complex motor performance. Results of regression modeling revealed that cognitive-neural variables explain a large proportion of variance in skill performance effectiveness, confirming that quality of athletic performance does not depend on physical characteristics alone, but is based on an integrated cognitive-neural foundation. Results showed that incorporating decision-making tasks, graded cognitive load, and micro-games into training programs leads to more stable learning and better transfer of performance to competitive situations. Study confirms that traditional training models that focus solely on technical repetition do not achieve maximum possible efficiency in motor learning compared to programs based on cognitive-neural foundations.

Recommendations

Adopting training programs based on cognitive-neural modeling in teaching and training volleyball in physical education colleges and sports clubs, due to their effective impact on developing skill performance and cognitive abilities. Incorporating cognitive-neural variables such as reaction time, executive control, and working memory into sports preparation programs and considering them as key indicators for evaluating player progress. Training trainers and teachers on use of strategies for directing external attention, organizing feedback, and designing training situations with progressive cognitive load. Expanding scope of future research to include different age groups and competitive levels, and using advanced neuromeric tools EEG, fNIRS to study neurological changes associated with motor learning. Conducting longitudinal studies to monitor sustainability of impact of cognitive-neuropsychological programs on competitive performance in long term.

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