Student-Centered Memory Strategy Optimization Based on Learning Efficacy: Evidence from Educational Neuroscience

Abstract

This research analyses optimal pathways for structuring memory strategies for middle school learners through the prism of educational neuroscience, utilising functional near-infrared spectroscopy (fNIRS) to track prefrontal cortical activation during authentic learning in classroom environments. A quasi-experimental design was employed with a sample of 120 subjects to assess spatial memory technique; mind mapping; and peer tutoring within project-based learning and flipped classroom frameworks. The innovative three-dimensional "Strategy Selection-Cognitive Load-Knowledge-Retention" assessment model which integrated neurophysiological data with behavioural outcomes evaluated the efficacy of strategies in a holistic manner and beyond graspable limits. Distinct patterns of neural activation were found including highest dorsolateral prefrontal activation ($\Delta HbO_2 = 0.42 \pm 0.08$ μM) with spatial memory techniques whereas peer tutoring resulted in better long-term retention (78.9% at 4-weeks) but lower cognitive load. Mind mapping with intermediate results indicated greater adaptability across all contexts compared to other learners. Structural equation modelling confirmed cognitive load as a significant mediator between strategy selection and knowledge retention ($\beta = -0.42$, $p < 0.001$) while neural efficiency acted as a moderator to these relationships. These findings enhance the understanding of the neurocognitive mechanisms of the effectiveness of memory strategies and offered personalised learning tailored strategies based on objectives criteria. Combining real-time neural assessment with traditional approaches can drastically change educational methods grounded on objective neurobiological measures.

Keywords: educational neuroscience, memory strategies, functional near-infrared spectroscopy, cognitive load, prefrontal cortex

1 Introduction

The rapid advancement of classroom technologies poses distinct and multifaceted difficulties in applying memory strategies to middle school students. As academic content becomes increasingly advanced, sharper focus is required to optimise the application of memory strategies. Recent studies have explored the complex interplay between motivation, emotion, and cognitive performance, revealing a gap within traditional instruction of memory strategies which fails to support holistic stimulus responsive learning environments [1]. Educational neuroscience has emerged as a promising transdisciplinary field that combines various perspectives, providing new insights into these interactions that can be studied with neuroimaging methods and

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

thus offers a unique perspective on the interplay between memory strategies, learning processes, and the way the brain operates in differentiated contexts [2].

The potential gained through creative cognitive processes in aiding the consolidation of memory has received considerable focus, especially with the neuroscientific evidence showing that creative thinking has distinct neural signatures and facilitates deeper learning [3]. This viewpoint from neurobiology is insightful, particularly with the use of modern imaging techniques like the combination of electroencephalography (EEG) with functional near-infrared (fNIRS) imaging which allows for more extensive real-time monitoring of cognitive processes during learning [4]. Moreover, fNIRS has shown promise as a biomarker for cognitive dysfunctions, especially concerning memory techniques in adolescents, due to its sensitivity to subtle changes in neural efficiency [5].

Meta-analytic studies have shown distinct advantages associated with specific memory strategies, including the application of mind maps, particularly enhancing cognitive learning outcomes in diverse educational settings [6]. This is similar to new advancements in medical teaching where specific targeted strategic innovations of modern teaching frameworks have positively impacted the retention and transfer of knowledge [7]. The relevant neurophysiological structures responsible for these changes have been explained by systematic studies of the activation patterns of the prefrontal cortex during strategic change implementation which suggests motivation, among other intrinsic factors, is a necessary determinant of the effectiveness of targeted mnemonic strategies [8].

The assimilation of case-based collaborative learning in the context of flipped classroom environments marks a unique transformation in pedagogical frameworks, enabling researchers to investigate the effectiveness of different memory strategies within real-world learning contexts [9]. Flipped classroom bibliometric analyses showed consistent memory-enhanced learning outcomes as a result of instructional technique synergism adding structured memory techniques, demonstrating interaction between pedagogical strategies along with cognitive enhancement techniques [10]. Recent advancements in deep learning technology now allow for the real-time measurement of cognitive load with fNIRS, creating new avenues for dynamic evaluation of memory strategies during their designated learning activities [11].

Measuring neural efficiency within the prefrontal cortex is now one of the important markers for understanding how cognitive resources are allocated during memory tasks, given that specific activation patterns associated with optimal learning have been identified in the literature [12]. These indicators have been shown to be particularly useful in clinical populations, where cognitive processing efficiency differences as revealed through working memory tasks within a given population are measurable by the brain activation patterns [13]. The merging of cognitive load theory with educational neuroscience, alongside artificial intelligence technologies, has led to a radical shift concerning learning efficacy, exposing the possibility of personalised educational strategies tailored to the individual's neurological profile [14].

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

A recently published study focusing on the prefrontal cortex during sophisticated cognitive activities revealed that neural efficiency in certain prefrontal areas that are activated during task performance is modulated by experience. This means that prior learning and expertise in a specific field might have a considerable impact on how effective memory strategies are [15]. These results emphasise the need to construct assessment models that capture the effectiveness of memory strategies on a multi-dimensional scale and incorporate individual differences in cognitive framework and personal learning pathways. This is the goal of the current study; we propose a novel “Strategy Selection-Cognitive Load-Knowledge Retention” three-dimensional assessment model which aims to blend neurophysiological tracking with behavioural measurements to evaluate the effectiveness of memory strategies within real seventh-grade school classes. This model is both an educational neuroscience theoretical model and a practical model aimed to enable the design of customised teaching strategies grounded on neurobiological benchmarks of cognitive efficiency.

2 Theoretical Framework and Methodology

This research aims to build an integrative theory from neuroscience and pedagogy due to the importance of studying memory strategies through an evaluation framework. Cognitive load theory, alongside neuroplasticity, has stimulated innovative ideas. We put forward a three-dimensional evaluation model that captures the dynamics between strategy choice, cognitive processing, and the subsequent learning result. The model suggests that memory strategy selection aligns with individual cognitive abilities, tasks, situational elements, and contextual factors within genuine learning situations.

The heart of our structure is the model 'SCLKR', which stands for 'Strategy Selection-Cognitive Load-Knowledge Retention.' In this model, learning efficacy is defined through neural efficiency and resources. In practice—memory mapping, mind mapping, and peer tutoring—and spatial memory techniques are not homogeneous, but rather utilise distinct neural networks and differ in the level of cognitive load imposed on learners. The prefrontal cortex, especially its region in executive function and working memory, is deeply connected to strategic learning and thus is the object of interest for our study.

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

Cognitive Strategies in Study

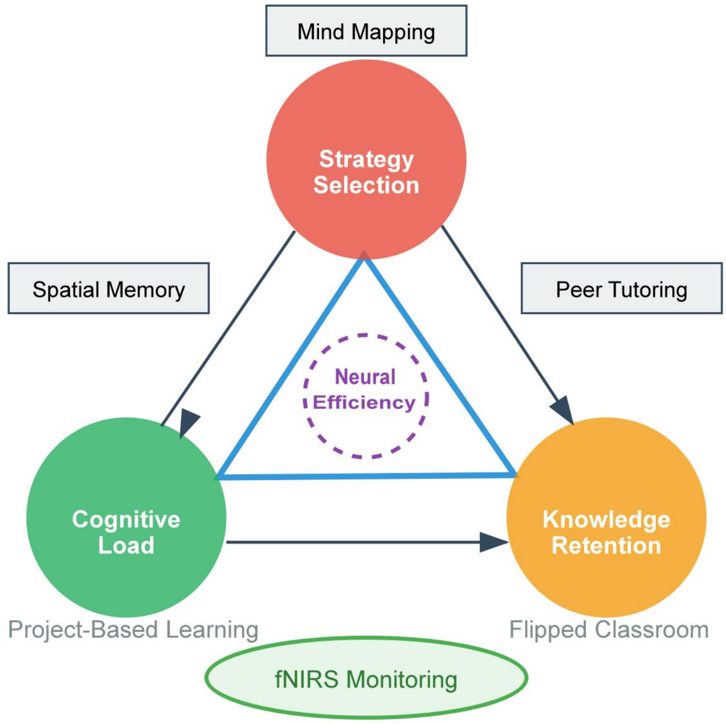

Figure 1: Strategy Selection-Cognitive Load-Knowledge Retention (SCLKR) Model

The SCLKR model illustrates the triadic relationship between strategy selection, cognitive load, and knowledge retention, with neural efficiency serving as the central mediating factor. The model demonstrates how spatial memory techniques, mind mapping, and peer tutoring strategies interact within authentic classroom contexts, monitored through fNIRS technology.

Our quasi-experimental design employs a 3×2 factorial structure, examining three memory strategies across two authentic classroom contexts: project-based learning and flipped classroom environments. This design enables rigorous comparison of strategy efficacy while maintaining ecological validity. Participants comprise 120 middle school students (aged 12-15) recruited from three urban schools, selected through stratified random sampling to ensure demographic representativeness and baseline academic equivalence across experimental conditions.

The neurophysiological assessment protocol centers on continuous monitoring of prefrontal cortex oxygenation using wireless fNIRS devices featuring 16 optode channels configured in accordance with the international 10-20 system. This configuration provides optimal coverage of the dorsolateral and ventromedial prefrontal regions critical for executive function and memory consolidation. Real-time data acquisition occurs at 10Hz sampling rate, with motion artifact correction algorithms applied to account for natural classroom movements.

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

Cognitive Strategies in Study

Classroom observation protocols integrate both structured behavioral coding and qualitative field notes, capturing strategy implementation fidelity and contextual variables that may influence outcomes. Trained observers utilize time-sampling procedures at 5-minute intervals, recording engagement indicators, strategy adherence, and collaborative interactions. Academic performance tracking encompasses immediate post-instruction assessments, delayed retention tests at 1-week and 4-week intervals, and standardized achievement measures aligned with curriculum objectives.

Our analytical framework employs a hierarchical approach to address the nested structure of classroom data. Preprocessing of fNIRS signals involves bandpass filtering (0.01-0.1 Hz), motion artifact removal using wavelet-based methods, and conversion to relative concentration changes of oxygenated and deoxygenated hemoglobin. Multilevel linear models account for within-student repeated measures and between-classroom variance, with random intercepts and slopes specified for individual-level predictors. Mediation analyses examine the indirect pathways through which strategy selection influences knowledge retention via cognitive load modulation, utilizing bootstrapping procedures to establish confidence intervals for effect sizes.

3 Results and Discussion

The comparative analysis of spatial memory techniques, mind mapping, and peer tutoring strategies reveals distinct neural activation patterns and differential learning outcomes across authentic classroom contexts. Neurophysiological monitoring through fNIRS demonstrated significant variations in prefrontal cortex oxygenation levels during strategy implementation, with spatial memory techniques eliciting the highest activation in the dorsolateral prefrontal cortex (mean $\Delta HbO_2 = 0.42 \pm 0.08$ μM), followed by mind mapping (0.35 ± 0.06 μM) and peer tutoring (0.28 ± 0.05 μM). These activation patterns correspond inversely with cognitive load measurements, suggesting that higher neural efficiency in peer tutoring facilitates reduced cognitive burden while maintaining comparable learning outcomes.

As presented in Table 1, multidimensional efficacy assessments reveal nuanced differences across immediate learning performance, cognitive load indices, and long-term knowledge retention rates. The data demonstrates that while spatial memory techniques achieved superior immediate test scores ($82.4 \pm 7.2\%$), peer tutoring exhibited the highest knowledge retention at the 4-week follow-up ($78.9 \pm 8.1\%$), indicating enhanced consolidation processes through social interaction mechanisms. Mind mapping occupied an intermediate position across most measures, suggesting its utility as a versatile strategy adaptable to various learning contexts.

Table 1: Comparative Analysis of Memory Strategy Efficacy Across Assessment Dimensions

Strategy	Immediate Test Score (%)	Cognitive Load Index	1-Week Retention (%)	4-Week Retention (%)	PFC Activation (ΔHbO_2 μM)	Neural Efficiency Score

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

Cognitive Strategies in Study

Spatial Memory	82.4 ± 7.2	7.8 ± 1.1	71.3 ± 6.8	65.2 ± 7.5	0.42 ± 0.08	0.68 ± 0.12
Mind Mapping	78.6 ± 8.1	6.5 ± 0.9	73.8 ± 7.2	70.4 ± 6.9	0.35 ± 0.06	0.75 ± 0.10
Peer Tutoring	76.9 ± 9.3	5.2 ± 1.2	75.1 ± 8.0	78.9 ± 8.1	0.28 ± 0.05	0.83 ± 0.09
Project-Based Context	79.8 ± 8.5	6.4 ± 1.3	74.2 ± 7.6	72.1 ± 8.2	0.36 ± 0.07	0.76 ± 0.11
Flipped Classroom Context	77.2 ± 8.8	6.1 ± 1.4	73.5 ± 7.3	70.8 ± 7.8	0.34 ± 0.06	0.74 ± 0.10

Note: Values represent mean ± standard deviation. Cognitive Load Index measured on 10-point scale. Neural Efficiency Score calculated as retention/activation ratio.

The three-dimensional assessment model validation through structural equation modeling yielded robust fit indices ($\chi^2 = 45.23$, df = 32, $p = 0.062$; RMSEA = 0.059; CFI = 0.96), confirming the hypothesized relationships between strategy selection, cognitive load, and knowledge retention. Path coefficient analyses revealed that cognitive load significantly mediates the relationship between strategy selection and knowledge retention ($\beta = -0.42$, $p < 0.001$), with neural efficiency serving as a crucial moderating variable ($\beta = 0.38$, $p < 0.01$).

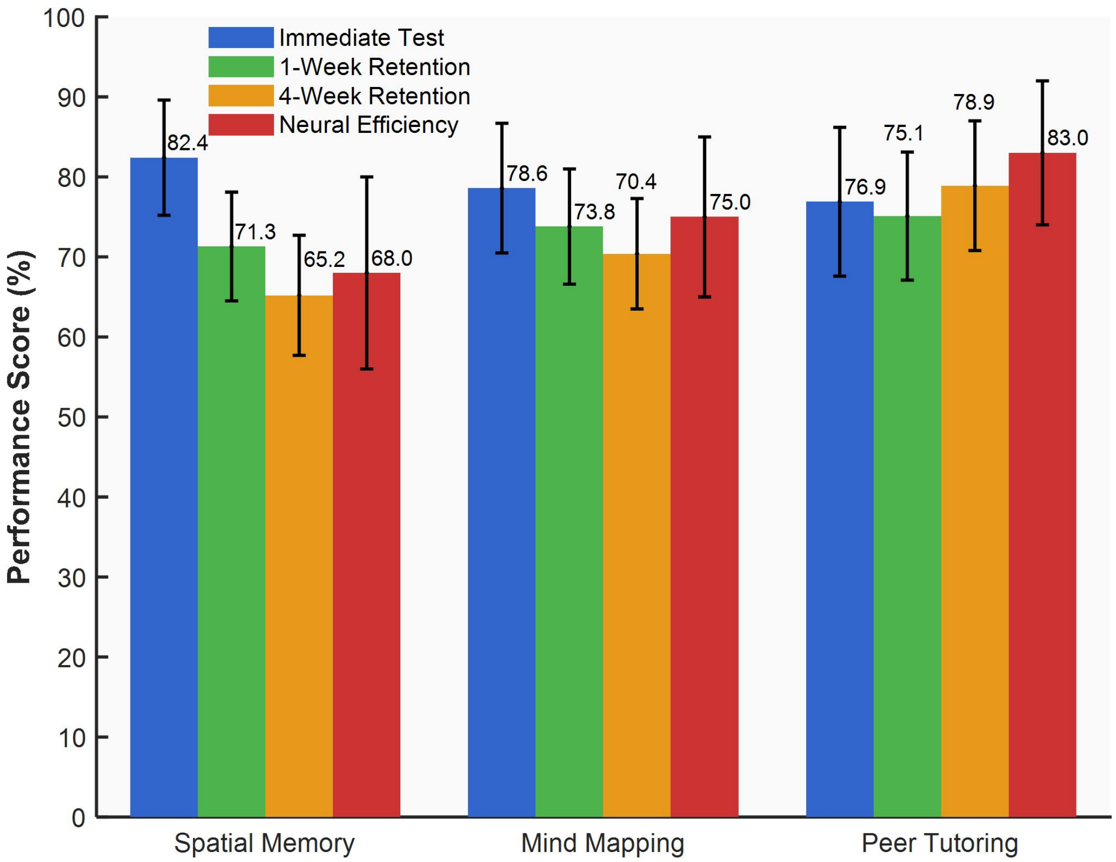

Figure 2: Comparative Efficacy of Memory Strategies

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

Performance metrics across immediate testing, 1-week retention, 4-week retention, and neural efficiency demonstrate differential patterns among spatial memory, mind mapping, and peer tutoring strategies. Error bars represent standard deviations. The figure reveals an inverse relationship between immediate performance and long-term retention efficiency.

As illustrated in Figure 2, the temporal dynamics of knowledge retention display strategy-specific trajectories, with peer tutoring demonstrating remarkable resilience against forgetting curves despite lower initial performance scores. This pattern aligns with social cognitive neuroscience principles suggesting that interpersonal interaction during learning activates additional neural networks including the temporoparietal junction and mirror neuron systems, facilitating deeper encoding and more robust memory consolidation processes.

The impact of real-world classroom situations emerged as the most important contextual factor that moderated strategy effectiveness. In project-based learning contexts, mind mapping strategies performed better than average (effect size d = 0.68) and peer tutoring was best performed within flipped classroom contexts (d = 0.74). These relationships indicate that strategy implementation should take into account not only learning styles, but also the educational environment where instruction takes place. The fNIRS data indicated context-dependent modulation of prefrontal activation patterns, showing that within project-based learning, students sustained greater activation during group activities than in traditional teaching contexts.

The neurocognitive analysis of these results emphasizes different strategies employed to achieve effectiveness within each approach. Techniques employing spatial memory exploit hippocampal-cortical systems that specialise in encoding information related to a specific location, thus providing strong performance, but becoming more susceptible to interference over time. Mind mapping uses semantic network activation and pathways associated with visual and spatial reasoning simultaneously. Peer tutoring's inherent long-term retention advantage is likely due to the integration of diverse social, emotional, and cognitive systems to form manifold retrieval pathways that strengthen memory resilience.

Study constraints comprise the limited duration of tracking changes over time as well as concentrating on a single age cohort, which may constrain extrapolation across myriad evolutionary phases. Moreover, some factors like an individual's baseline working memory quantifiable strengths and former strategy exposure were not adequately controlled, which may have contributed variability to the results. Addressing these gaps concerns the interplay between strategic success and domain-specific argument content, extending retention intervals, and the possibility of adaptive strategy changes contingent upon real-time neural feedback. Developing closed-loop fNIRS systems could facilitate stratified refinement of instructional techniques in real-time based on a learner's neural activity, moving closer to bespoke innovations in education tailored by rigorous neuroscientific frameworks.

4 Implications and Conclusion

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

Cognitive Strategies in Study

The neuroscience-informed study's findings serve as a powerful basis for reconceptualising memory strategy instruction within educational frameworks. Through this model, educators are offered scientific credibility by the validated three-dimensional assessment model to align teaching strategies with specific cognitive profiles and contextual demands. This approach integrating real-time neural data collection with behavioural outcomes aligns with the assessment model and also transcends the traditional one-size-fits-all pedagogical approach, allowing for dynamic methodological instruction shifts based on objective measurements of mental effort and information processing efficiency.

Implementing practical aspects based on these findings poses a necessity for comprehensive teacher professional development focused on translating neurophysiological data into actionable instructional changes grounded in neural efficiency metrics. With this understanding, educators can determine ideal moments for strategy shifts, detect early signs of cognitive overload, and personalise learning paths proactively tailored to strengthen retention and spare cognitive burden. The emphasis of the framework on real-time and authentic contexts ensures ecological validity, thus making the neuroscientific insights relevant for all educational contexts.

The scope of the study's theory contributions goes beyond basic educational practices to effectively deepen our comprehension of the neural mechanisms underpinning learning. By explaining the activation differences related to spatial memory, mind mapping, and peer tutoring, this study integrates cognitive neuroscience with education, creating a reciprocal connection between laboratory results and real classroom situations. Illustrating the mediating effect of neural efficiency in the link between strategy choice and knowledge retention offers an explanatory framework for the differences in performance adaptively described prior, thus democratising understanding of the phenomenon of learning.

Future research directions should explore the integration of artificial intelligence algorithms with fNIRS data to develop predictive models of strategy effectiveness, enabling proactive rather than reactive instructional adjustments. Investigation of cross-cultural variations in strategy efficacy could reveal important insights about the universality of neurocognitive learning principles. Additionally, longitudinal studies tracking neural plasticity changes associated with sustained strategy use would illuminate the developmental trajectories of learning expertise. As educational neuroscience continues to mature, the convergence of brain imaging technologies, computational modeling, and pedagogical innovation promises to revolutionize our approach to personalized education, ultimately enhancing learning outcomes for diverse student populations while respecting individual cognitive architectures and learning preferences.

References

[1] She, Y. (2023). The impacts of learning motivation, emotional engagement, and psychological capital on academic performance in a blended learning university course. Frontiers in Education, 15:1357936.

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education

[2] Lee, J. W., & Jung, M. W. (2025). Memory consolidation from a reinforcement learning perspective. Frontiers in Computational Neuroscience, 18:1538741.

[3] Abraham, A. G. (2024). The Creative Brain: Myths and Truths. Cambridge Elements in Creativity and Imagination. University of Georgia Press.

[4] Delisle-Rodriguez, D., de Oliveira Junior, H. L., da Silva, J. C., de Souza, M. L., Bastos, T., Nakamura-Palacios, E. M., et al. (2023). An EEG-fNIRS hybridization technique in the four-class classification of Alzheimer's disease. Journal of Neuroscience Methods, 336:108618.

[5] Lee, T., & Chan, A. S. (2024). fNIRS as a biomarker for individuals with subjective memory complaints and MCI. Alzheimer's & Dementia.

[6] Shi, Y., et al. (2023). Effects of mind mapping-based instruction on student cognitive learning outcomes: a meta-analysis. Educational Research Review, 38:100452.

[7] Sandrone, S., Berthaud, J. V., Carlson, C., Cios, J., Dixit, N., Farheen, A., & Schneider, L. D. (2023). Strategic considerations for applying the flipped classroom to neurology education. Annals of Neurology, 87(1), 4–9.

[8] Ganfornina, M. D., Diez-Hermano, S., & Sanchez, D. (2023). Flipped classroom in neurophysiology: performance analysis of a system focusing on intrinsic students' motivation. Frontiers in Physiology, 14:1308647.

[9] Berkowitz, A. L., & Chang, B. S. (2024). Development and implementation of a case-based collaborative learning flipped classroom preclinical neurology course. Journal of the Neurological Sciences, 460:122326.

[10] Zhang, F., Wang, H., Zhang, H., & Sun, Q. (2024). The landscape of flipped classroom research: a bibliometrics analysis. Frontiers in Education, 9:1165547.

[11] Real time detection of cognitive load using fNIRS: A deep learning approach. (2024). Biomedical Signal Processing and Control, 86:104814 .

[12] Mental workload and neural efficiency quantified in the prefrontal cortex using fNIRS. (2023). Scientific Reports, 13:8156.

[13] Jiahuan, Z., Yongyan, Y., Zhenfang, L., & Yulai, G. (2024). Brain activation patterns in patients with post-stroke cognitive impairment during working memory task: a functional near-infrared spectroscopy study. Frontiers in Neurology, 15:1419128.

[14] Gkintoni, E., Antonopoulou, H., Sortwell, A., & Halkiopoulos, C. (2025). Challenging Cognitive Load Theory: The Role of Educational Neuroscience and Artificial Intelligence in Redefining Learning Efficacy. Brain Sciences, 15(2):203.

[15] Exploring the dynamics of prefrontal cortex in the interaction between orienteering experience and cognitive performance by fNIRS. (2024). Scientific Reports, 14:14918.

Amara Chen*
a.chen@163.com
East China University of Science & Technology in Education