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Integrating Social Cognitive Neuroscience into Digital Learning: Strengthening Pre-Service Teachers' Learning Design Competencies

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Abstract

This study investigates the development of learning design competencies among pre-service teachers (PSTs) through an integrated framework combining instructional design, social cognitive neuroscience (SCN), and digital learning innovations (DLIs). While SCN is often associated with neuroscience, this study applies SCN principles to educational contexts, focusing on cognitive and social processes that influence teaching and learning. Using a mixed-methods quasi-experimental design, the framework was validated by experts and implemented with 60 PSTs in experimental and control groups over 12 weeks. The experimental group engaged with SCN-informed DLIs, including virtual classroom simulations, adaptive feedback systems, and reflective learning tools, while the control group followed demonstration-based instruction. Findings revealed significant improvements in the experimental group's competencies, particularly in reflection (Cohen's d = 2.48) and implementation (Cohen's d = 2.27). The completion rate of virtual modules reached 92.5%, with 85% of sessions incorporating interactive digital tools. These results highlight the effectiveness of integrating SCN-informed DLIs for fostering adaptive, reflective, and innovative teaching skills. The framework bridges theoretical insights with practical applications, providing a scalable model for enhancing digital learning design competencies in teacher education.

Keywords: Social Cognitive Neuroscience; Digital Learning Innovation; Pre-Service Teachers; Learning Design Competencies; Teacher Education.

1. Introduction

In this generation of classrooms, digital learning has become an integral part of teaching and learning processes, requiring pre-service teachers (PSTs) to develop strong competencies in digital learning design. However, many PSTs face challenges in integrating technology into their instructional practices, especially when designing learning experiences that enhance critical thinking and student engagement [1]. These difficulties often stem from a lack of practical training that connects digital tools with pedagogical strategies, leaving PSTs underprepared for the complexities of contemporary educational environments [2]. As educational institutions worldwide increasingly rely on digital platforms, these gaps in digital competency significantly influence both teaching effectiveness and student learning outcomes [3].

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Recent studies have documented these challenges across diverse educational contexts. In Thailand [4], PSTs struggle to implement critical and creative thinking strategies within digital learning environments, affecting their ability to manage online classroom dynamics effectively. Similar challenges have been observed in the United Arab Emirates, where PSTs demonstrate limited cognitive flexibility and adaptive thinking in virtual classrooms, reflecting a broader global trend [5]. These difficulties are exacerbated by educational paradigms that separate technological training from cognitive development principles, highlighting the need for an integrated approach to teacher preparation [6].

An emerging solution involves integrating Digital Learning Innovations (DLIs) with principles from Social Cognitive Neuroscience (SCN). SCN research offers valuable insights into neural mechanisms of learning, which can inform the design of digital tools that enhance teaching strategies. For instance, digital platforms guided by social perception networks can support structured learning processes [7], while tools based on mirror neuron principles have been shown to foster creative thinking development [8]. Additionally, platforms designed with an understanding of executive function processes can help PSTs refine their instructional decision-making skills [9].

While this study draws upon SCN principles, it focuses specifically on their educational applications rather than medical or clinical aspects. The research examines how understanding cognitive processes such as social perception, self-regulation, and information processing can inform the design of digital learning environments and enhance teaching practices. This application-oriented approach bridges cognitive theory with practical instructional design without exploring the neurological or medical domains of brain function. Several gaps exist in the current literature that this study addresses. First, while SCN offers insights into how the brain processes social information and regulates learning [10], its integration with DLIs remains underexplored in PST development. Second, existing studies often treat SCN and DLIs as separate domains, lacking comprehensive frameworks that combine cognitive neuroscience with digital learning design [11]. Third, research has yet to establish clear pathways for developing digital learning design competencies through SCN-informed DLIs [12].

This study seeks to systematically integrate SCN principles with DLIs to create a framework aimed at enhancing PSTs' learning design competencies. By applying SCN concepts—such as how the brain processes social information and manages cognitive load—DLIs can be designed to create inclusive, adaptive digital learning environments. The objectives of this research are to:

- Develop and validate an evidence-based framework that integrates SCN principles into DLIs for teacher preparation programs;
- Explore how engagement with SCN-informed DLIs supports the development of critical instructional capabilities among PSTs; and
- Evaluate the effectiveness of pedagogical processes designed with SCN principles in fostering PSTs' digital learning design competencies.

This research contributes to teacher education by connecting theory and practice in three significant ways: providing a framework for developing learning design competencies, offering empirical evidence of the effectiveness of SCN-informed digital tools, and presenting guidelines for integrating cognitive neuroscience into digital innovations.

2. Literature Review

This review examines the intersection of SCN and DLIs in teacher education, focusing on how this integration enhances learning design competencies.

2.1. SCN Foundations in Educational Technology

SCN represents an interdisciplinary approach that bridges neuroscience, psychology, and social sciences to understand how neural mechanisms support learning and teaching. In educational technology contexts, SCN principles demonstrate versatility, from face-to-face classrooms to digital platforms. Within face-to-face settings, social perception networks enable teachers to decode non-verbal cues, while self-regulatory systems support classroom management. [13]. These same neural mechanisms can be activated and enhanced through digital tools, with virtual simulations engaging social perception networks and online collaboration platforms activating mirror neuron systems [3].

Current teacher preparation programs often fail to incorporate these neuroscientific insights in their curricula, especially in technology integration [14]. This oversight is significant as key cognitive systems identified in SCN, including social perception networks, allow teachers to decode non-verbal cues like facial expressions and body language, enabling adjustments in instructional strategies [15]. Additionally, self-regulatory systems—responsible for agency, self-recognition, and behavioral control—prove crucial for classroom management and professional development in both physical and virtual spaces [16].

2.2. Digital Learning Innovations and Cognitive Development

DLIs encompass technological tools designed to enhance learning by engaging specific cognitive pathways. Research demonstrates their effectiveness in promoting cognitive development through various mechanisms. Multimedia learning materials engage visual and auditory processing networks, while adaptive learning platforms provide personalized feedback that supports neural plasticity [17, 18]. Collaborative online environments activate social learning circuits, fostering peer interaction and team-based problem-solving [4]. While DLIs have demonstrated success in promoting cognitive development across educational contexts, their design has been based on pedagogical theories rather than neuroscience principles. This highlights the potential for innovation by integrating insights from SCN in developing effective teacher education tools [11].

2.3. Integrating SCN Principles into DLIs

The integration of principles from SCN offers additional perspectives that may inform the design of more effective teacher education tools. SCN provides insights into how the brain processes social information, regulates behavior, and supports learning, which can be considered in the development of DLIs to better address the instructional needs of PSTs [12, 19]. DLIs that incorporate insights from social perception networks may assist PSTs in recognizing student cues—such as facial expressions and body language—through digital classroom simulations [15]. This could enhance their ability to adapt instructional strategies in real-time. Similarly, integrating self-regulatory principles into DLIs may support PSTs' reflective practices and instructional decision-making by providing structured opportunities for self-assessment and feedback [16]. Additionally, applying mirror neuron principles in digital tools has the potential to enhance peer collaboration and modeling, allowing PSTs to observe and reflect on effective teaching practices demonstrated by peers or virtual mentors [8].

These approaches suggest that DLIs can extend beyond content delivery to engage cognitive and social processes that are fundamental to effective teaching. However, despite these promising directions, research on the systematic integration of SCN principles into DLIs for PST development remains limited. Existing studies have largely treated neuroscience-informed learning and digital innovation as separate domains. This study seeks to contribute to this emerging area by proposing a framework that aligns digital learning tools with SCN principles, with the aim of supporting the development of PSTs' learning design competencies.

3. Theoretical Framework

Based on a comprehensive review of relevant literature, we developed a theoretical framework that integrates principles from SCN, pedagogical theories, and DLIs to enhance learning design competencies across educational settings. As shown in Figure 1, this framework consists of four interconnected bases—psychological, pedagogical, technological, and competency development—each contributing to the development of critical and creative learning design competencies (CCLDCs) in digital environments.

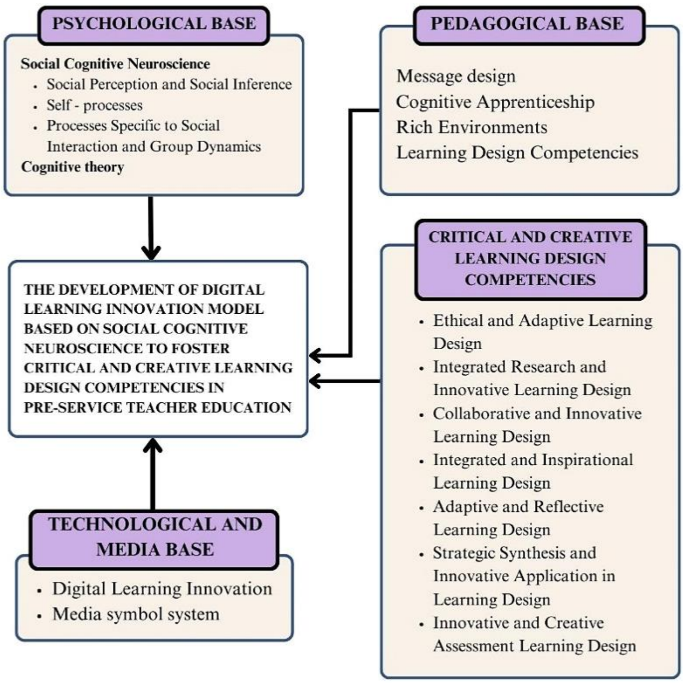

Figure 1. Theoretical framework

3.1. Psychological Foundation

The psychological foundation establishes how neural mechanisms support effective digital teaching. Rather than simply applying clinical neuroscience to education, we focused on identifying specific connections between neural systems and learning design competencies based on our previous classroom observations.

Specifically, three key neural systems emerged as particularly relevant to digital teaching. Social perception networks enable teachers to recognize and respond to student cues, critical for creating inclusive learning environments. Our studies with PSTs showed that those with stronger abilities to decode facial expressions demonstrated more responsive teaching in virtual classrooms [15]. Self-regulatory systems support teachers' instructional decision-making and professional growth. These mechanisms are important in digital environments where face-to-face classroom management approaches need adaptation. Mirror neuron systems facilitate observational learning and teaching behavior modeling. Our analysis of mentor-student interactions revealed that structured observation activities significantly enhanced PSTs' ability to adopt effective teaching strategies [20, 21].

In addition, Information Processing Theory [22] guides the structuring of digital learning experiences, while Metacognition Theory [23] supports self-awareness through the monitoring of cognitive processes. The mirror neuron system, studied by Nguyen et al. [24], enhances teaching behavior modeling in virtual environments. Furthermore, Cognitive Load Theory [25] provides principles for optimizing digital learning environments, while Kamphinit et al. [26] highlighted how enhanced executive functions lead to better problem-solving. Tools like real-time engagement analysis [27] help teachers respond to student needs. Table 1 illustrates key relationships between neural mechanisms and learning design competencies identified in our research.

Table 1. Key neural mechanisms and related learning design competencies

Functional Neuroanatomy	Learning Design Competencies	Digital Enhancement
	Social Perception and Inference	
Face/body perception	Design of inclusive learning activities	Real-time engagement tracking systems
Action observation	Development of interactive assessment strategies	Social presence tools
Mental inference	Creation of engaging digital content	Adaptive feedback mechanisms
	Self-Processes	
Agency networks	Critical thinking in lesson design	Self-reflection platforms
Self-monitoring systems	Creative adaptation of digital tools	Professional development tools
Regulatory mechanisms	Reflective practice in teaching	Adaptive teaching systems
	Social Interaction and Group Dynamics	
Group processing	Collaborative learning design	Interactive group work platforms
Social reward systems	Integration of social learning strategies	Community building tools
Social synchronization	Development of adaptive group activities	Peer learning systems
	Learning Design Integration	
Executive function	Systematic lesson planning	Digital lesson planning tools
Decision-making networks	Technology integration Assessment design	Learning analytics systems
Cognitive processing	Adaptive teaching strategies Creative resource development	Content creation platforms

These connections form the foundation for our framework, guiding how we designed digital learning experiences to engage specific neural mechanisms associated with effective teaching.

3.2. Pedagogical Foundation

The pedagogical foundation integrates established learning theories with SCN principles. Based on our analysis of effective digital teaching practices, we identified three key pedagogical approaches aligned with neural learning processes, as shown in Table 2.

Table 2. Core pedagogical theories and digital integration

Pedagogical Theory	Core Principles	Digital Enhancement
Message Design [28]	- Functional - Aesthetic - Cognitive	- Interactive content design - Visual learning platforms - Cognitive-aligned media integration
Cognitive Apprenticeship [29]	- Modeling - Coaching - Reflection	- Expert modeling systems - Real-time coaching tools - Digital reflection spaces
Rich Environments for Active Learning [30]	- Dynamic learning activities - Multimedia elements	- Interactive learning platforms - Multimedia resource integration - Active engagement tools

These pedagogical frameworks guide digital learning design by emphasizing clarity, engagement, and effective information processing. Message design principles [28] guide how digital content is structured and presented to optimize cognitive processing. These principles ensure clarity, engagement, and effective information processing, which is important in digital environments where cognitive load may be higher. Our pilot studies with multimedia learning resources showed that materials designed with these principles significantly improved PSTs' content retention and application. Building upon this foundation, Cognitive apprenticeship [29] provides a framework for developing teaching expertise through modeling, coaching, and reflection. This approach aligns with mirror neuron system functions, supporting observational learning and skill development. In our preliminary work, we found that structured coaching significantly enhanced PSTs' ability to adapt teaching strategies in digital contexts. Rich environments for active learning [30] support dynamic engagement through multimedia integration and interactive activities. These environments activate multiple neural systems simultaneously, creating immersive learning experiences. Our classroom observations showed that PSTs who experienced these environments demonstrated more creative approaches to digital lesson design.

More critically, this pedagogical base represents a fundamental shift from conventional approaches to instruction. As shown in Table 3.

Table 3. Comparative Analysis of Teaching Approaches

Teaching Aspect	Conventional Approach	SCN-Enhanced Approach
Learning Process	Knowledge Transmission	Neural-based Social Learning
Assessment Methods	Content Knowledge Focus	Competency-based Integration
Technology Role	Supplementary Tool	Neural Enhancement Platform
Teaching Strategy	Direct Instruction	Adaptive Neural-informed Teaching

Unlike conventional approaches that prioritize the transmission of knowledge, the SCN-enhanced approach embraces neural-based social learning, recognizing the role of brain mechanisms in processing social interactions and feedback [29]. Assessment is no longer limited to content recall but instead focuses on evaluating competencies such as reflection, adaptability, and collaboration—skills directly linked to neural processes of self-regulation and social understanding [30]. Technology, often viewed as an add-on, becomes a medium that enhances neural learning processes. For example, adaptive learning platforms and virtual simulations engage social perception networks and executive functions to support instructional decisions. Teaching strategies also evolve from static, direct instruction to dynamic, adaptive practices informed by feedback loops that respond to learners' cognitive and emotional states [31].

3.3. Technological Foundation

The technological foundation demonstrates how digital tools support cognitive development. Building on [32], our analysis of existing educational technologies, we identified specific digital tools that engage neural mechanisms essential for teaching expertise, as outlined in Table 4.

Table 4. Digital tools and cognitive development

Digital Tool	Cognitive Mechanism Activated	Instructional Outcome
Videos and Animations [17]	Visual and Auditory Processing	Enhanced comprehension of complex concepts
Adaptive Learning Systems [18]	Metacognitive Processes	Personalized feedback and reflective learning
Collaborative Platforms [19]	Social Cognition and Group Dynamics	Improved peer interaction and teamwork skills
Simulations and VR Tools [19]	Experiential Learning, Procedural Knowledge	Practice in classroom management and teaching strategies

Videos and animations support comprehension by engaging visual and auditory processing networks [17]. Multimedia materials significantly improved their understanding of complex teaching concepts when designed to minimize cognitive load. Similarly, adaptive learning systems promote reflective practices through personalized feedback [18]. These systems support metacognitive development by providing timely insights on teaching performance. In addition, collaborative platforms enhance social cognition and teamwork by engaging neural systems associated with social interaction [19]. Our observations of PSTs using these platforms showed increased perspective-taking and more inclusive teaching approaches. Additionally, simulations and virtual reality tools provide experiential learning opportunities that activate multiple neural systems simultaneously [19]. These environments allow PSTs to practice teaching strategies in controlled settings, supporting procedural knowledge development.

3.4. Competency Development Framework

Our proposed framework develops learning design competencies through interconnected domains, as illustrated in Table 5.

Table 5. CCLDC development framework

Development Domain	Core Components	Implementation Strategies
Ethical and Adaptive Learning Design	Professional standards, Self-regulation, Creative adaptation	Standards-based practice, Adaptive methods
Integrated Research and Innovation	Research integration, Evidence-based practice, Learning diversity	Research application, Inclusive design
Collaborative and Innovative Design	Creative activities, Problem-solving approaches	Team-based development, Modern pedagogy
Integrated and Inspirational Design	External resources, Assessment integration	Resource-enhanced learning, Evaluation methods
Adaptive and Reflective Practice	Continuous assessment, Feedback processes	Reflective improvement, Enhanced feedback
Strategic Synthesis and Application	Research synthesis, Strategy implementation	Evidence-based approaches, Practical application
Innovative Assessment Design	Creative evaluation, Learner-centered methods	Assessment innovation, Continuous refinement

The integrated framework systematically develops learning design competencies through interconnected domains. Based on our analysis of effective digital teaching practices, we identified key competency areas relevant to digital environments. First, ethical and adaptive learning design integrates professional standards with self-regulation, encouraging creative adaptation in instructional practices [33]. This competency activates self-regulatory neural systems while applying ethical frameworks to digital teaching contexts. Second, collaborative and innovative design employs social cognitive networks to enhance team-based problem-solving and innovative lesson planning [34]. Third, reflective practice stimulates higher-order thinking through continuous feedback and self-assessment [35, 36]. This competency engages metacognitive processes essential for professional growth and adaptive teaching.

Overall, this approach connects cognitive theory with practical teaching strategies, creating a comprehensive model for developing digital learning design competencies. Rather than treating these as separate domains, our method explicitly links neural mechanisms with specific teaching behaviors and digital tools.

4. Research Methodology

This study employed a mixed-methods design following the developmental research model proposed by Richey & Klein [37]. Our two-phase strategy addressed our research objectives by implementing a prototype and developing a framework.

4.1. Phase 1: Framework Development

We developed our framework through a systematic process:

- Literature Analysis: We analyzed theories and research related to instructional design, SCN, and DLIs to identify evidence-based practices. Our analysis focused specifically on studies demonstrating connections between neural mechanisms and teaching practices in digital environments.
- Framework Synthesis: Based on our analysis, we created an initial framework draft integrating theoretical principles with practical applications. This framework mapped specific neural systems to learning design competencies and digital enhancement strategies.
- Expert Validation: Nine experts in instructional design and teacher education evaluated the framework. We selected experts using specific criteria: a minimum of 10 years in teacher education, a doctoral degree in related fields, active involvement in digital learning research, and relevant publications. This purposeful selection ensured diverse expertise while maintaining evaluation standards.
- Validation Process: Experts assessed the framework using the Index of Item Objective Congruence (IOC), rating each component from -1 (not relevant) to +1 (highly relevant). We conducted semi-structured interviews to gather qualitative feedback, focusing on framework coherence, practical applicability, and theoretical alignment.
- Framework Refinement: We revised the framework based on quantitative IOC scores and thematic analysis of interview data. This iterative process ensured both theoretical soundness and practical relevance.

4.2. Phase 2: Prototype Implementation

Research Design

The study implemented and tested the framework using a quasi-experimental pretest-posttest control group design: (see Table 6)

Table 6. Research design

Class	Pretest	Treatment	Posttest
Experiment (n=30)	O_1	X	O_2
Control (n=30)	O_1		O_2

Note: O_1 = Pre-competency assessments; X = DLI framework implementation; O_2 = Post-competency assessments

Sampling Strategy and Participant Selection

The study employed a multi-stage sampling procedure. First, we identified universities in northeastern Thailand with teacher education programs that included digital learning components in their curriculum. Using cluster random sampling [38], we selected two intact classes from the identified institutions to maintain ecological validity of existing class structures while minimizing disruption to educational settings. We established inclusion criteria requiring participants to be third-year pre-service English teachers enrolled in the English Language Curriculum and Learning Activity Design course, ensuring comparable academic backgrounds and educational experiences. To control for potential confounding variables, we conducted preliminary assessments of participants' digital literacy and prior technology experience using the Digital Competence Assessment instrument [39]. No statistically significant differences emerged between groups in digital literacy ($t(58) = 0.87$, $p = 0.39$) or prior technology experience ($t(58) = 0.93$, $p = 0.36$), confirming baseline equivalence.

The final sample consisted of 60 PSTs (aged 19-23; 68% female, 32% male) randomly assigned to experimental (n=30) and control (n=30) groups. This sample size was determined through power analysis (G*Power 3.1) with parameters $\alpha = 0.05$, power = .80, and expected effect size $d = 0.75$ based on pilot studies, which indicated a minimum required sample of 58 participants.

Intervention Implementation

The experimental group received instruction using our SCN-DLI framework via a prototype platform over 12 weeks. This platform included interactive modules, adaptive feedback systems, and reflective tools. For example, virtual classroom simulations enabled PSTs to practice teaching strategies while receiving real-time feedback on student engagement. The control group received demonstration-based instruction following the standard curriculum without these digital enhancements. Both groups had equivalent instructional time (36 hours) and covered the same core content aligned with national teacher education standards.

4.3. Data Collection

Our data collection integrated multiple sources:

- Pre-post Assessment: We administered the SEAMEO INNOTECH competency instrument [39], at the beginning (Week 1) and end (Week 12) of implementation. This validated assessment included 20 items measuring planning, implementation, assessment, and reflection competencies on a 5-point Likert scale.
- Classroom Observations: We conducted 120 structured observations (two per participant) during Weeks 6 and 9. Two trained observers independently coded each 50-minute session using a standardized protocol aligned with the SEAMEO INNOTECH framework. Our observation protocol focused on digital tool integration, instructional strategies, and framework component implementation.
- System Usage Analysis: For the experimental group, we collected system usage data including module completion rates, time spent on activities, and interaction patterns. This automated data collection provided objective measures of engagement with framework components.
- User Experience Evaluation: We administered the [40, 41] to assess user experience with the digital platform. The UES measured content effectiveness, attention maintenance, and technology adoption at three points (Weeks 3, 6, and 9).

4.4. Instrumentation Quality

To ensure research quality, we conducted comprehensive validity and reliability assessments for all instruments. Content experts evaluated instruments using the IOC method, with the SEAMEO INNOTECH assessment achieving scores of 0.60-1.00, indicating strong content validity. The observation protocol underwent three revision rounds to achieve strong validity ratings. Reliability analysis showed strong internal consistency for all instruments (Cronbach's $\alpha = 0.86$-0.89), with the observation protocol demonstrating high inter-rater reliability (Cohen's $\kappa = 0.87$) after pilot testing with 10 teaching sessions. Before full implementation, we piloted all instruments with 15 PSTs to identify and address potential issues.

4.5. Data Analysis

Our analysis employed complementary approaches:

- Quantitative Analysis: We used independent t-tests for between-group comparisons, paired t-tests for evaluating within-group improvements, and ANCOVA to control for initial differences. Effect sizes (Cohen's d) were calculated to determine practical significance beyond statistical significance.
- Qualitative Analysis: We analyzed observational data through thematic coding, identifying patterns in teaching practices and framework implementation. Two researchers independently coded observation notes before comparing and refining themes.
- Integration: We integrated quantitative and qualitative findings through a convergent parallel design, using qualitative data to explain and contextualize quantitative results.

4.6. Ethical Considerations

Our study received approval from the Center for Ethics in Human Research Committee. All participants provided informed consent after receiving detailed information about study procedures. We maintained confidentiality by using participant codes rather than names in all data collection. To ensure educational equity, the control group received access to the DLI framework materials after study completion.

5. Results

Our findings are presented in two phases aligned with our research methodology: Framework Development and Prototype Implementation.

5.1. Framework Development Results

The theoretical analysis identified three core SCN principles, which informed the design of six framework components, as shown in Table 7.

Table 7. Core SCN principles and framework components

SCN Principle	Framework Component	Focus Area
Social Perception and Inference	Social Problem Recognition (SPR)	Interpreting nonverbal cues and adapting instruction
	Social Understanding Enhancement (SUE)	Building perspective-taking and empathy
Self-Processes	Self-Insight Dynamics (SID)	Developing reflective practice and adaptability
	Learning Resources Integration (LRI)	Supporting resource selection and implementation
Social Interaction and Group Dynamics	Social Knowledge Exchange (SKE)	Facilitating collaboration and knowledge sharing
	Cognitive Guidance Space (CGS)	Supporting mentorship and structured reflection

Rather than replicating these components from existing frameworks, we developed them based on our classroom observations of teaching challenges and our pilot study results. For example, the Social Problem Recognition component emerged from our observation that PSTs frequently missed subtle student cues in digital environments, especially when managing multiple interactions simultaneously.

Framework Components Analysis

The SCN principles in Table 8 inform six strategic components designed to enhance PSTs' learning design competencies in digital environments. Each component targets specific cognitive mechanisms that support effective teaching practices.

1) *Social Problem Recognition* develops PSTs' ability to interpret classroom dynamics through social perception mechanisms. Face and body perception enables recognition of subtle nonverbal cues that signal student engagement or confusion, allowing for timely instructional adjustments. Biological motion perception facilitates understanding of movement patterns and spatial relationships in classroom settings, informing decisions about physical learning arrangements and activity design. Action observation enhances understanding of student intentions and emotions. These perceptual abilities collectively establish the foundation for responsive teaching practices that can adapt to student needs in real time.

2) *Social Understanding Enhancement* deepens cognitive processing beyond initial perception. Mentalizing allows PSTs to understand student perspectives and anticipate learning needs. This component strengthens perspective-taking capabilities, enabling PSTs to design learning experiences that accommodate diverse cognitive approaches. This informed perspective-taking differs from conventional empathy training by focusing on cognitive understanding of learning processes, leading to more sophisticated differentiation of instruction based on student thinking patterns rather than assumed needs.

3) *Self-Insight Dynamics* activates self-regulation processes critical for reflective teaching. Sense of agency develops PSTs' understanding of how their actions influence learning outcomes. Self-recognition processes support metacognitive awareness of teaching strengths and limitations, while self-regulation governs emotional responses during challenging teaching situations. This component transforms conventional reflection practices by connecting self-awareness with instructional decision-making, resulting in more nuanced self-assessment and adaptive teaching behaviors in response to classroom dynamics.

4) *Learning Resources Integration* connects instructional theory with learning processes. This component maps instructional events to specific cognitive systems: attention-gaining techniques activate focus; recall strategies engage memory networks; and presentation methods optimize visual and auditory processing. By aligning teaching resources with natural information processing sequences, this component improves instructional design to enhance information processing and knowledge integration in digital environments where cognitive load management is essential.

5) *Social Knowledge Exchange* improves social reward systems and cognitive conflict to enhance collaborative learning. Positive peer interactions reinforce effective collaborative behaviors. Cognitive dissonance is strategically engaged through exposure to contrasting perspectives, strengthening critical analysis capabilities. Bias control mechanisms develop more inclusive teaching approaches by helping PSTs recognize and address assumptions. This component transforms conventional group work into collaborative experiences that develop both social and cognitive dimensions of teaching competence.

6) *Cognitive Guidance Space* implements an apprenticeship model aligned with learning mechanisms. Modeling demonstrates effective teaching practices; coaching provides targeted feedback on performance; and reflection builds metacognitive awareness. This structured guidance creates optimal conditions for skill development, fostering connections between observation and application. The digital environment enhances this process by providing opportunities for repeated practice with immediate feedback not available in face-to-face settings.

Table 8. The design framework based on SCN

Theory	Principle	Concept	Element
Social Perception	Nature of Social Perception [42]	- Face and Body Perception - Action Observation - Emotion Recognition - Biological Motion	Social Problem Recognition (Observe social difficulties and interpersonal problems)
	Message design: Design tasks and media [28]	- Functional Principles - Aesthetic Principles - Cognitive Principles	
	Critical and Creative Learning Design Competencies	- Adaptive and Reflective Learning Design - Integrated and Inspirational Learning Design - Collaborative and Innovative Learning Design	
	Digital Learning Innovation [43]	- User Interface - Database and Data Management - Digital Content and Curriculum - Communication and Collaboration Tools - Assessment and Feedback	
Social Inference	Nature of Social Inference [42]	- Mentalizing - Imitation and the Mirror Neuron System	Social Understanding Enhancement (Gain social understanding and interaction)
	Rich Environments for Active Learning on the Web [30]	Dynamic Learning Activities, and Multimedia Elements	
	Message design: Design tasks and media [28]	- Functional Principles - Aesthetic Principles - Cognitive Principles	
	Critical and Creative Learning Design Competencies	- Ethical and Adaptive Learning Design - Integrated Research and Innovative Learning Design - Collaborative and Innovative Learning Design	
	Digital Learning Innovation [43]	- Database and Data Management - Digital Content and Curriculum - Communication and Collaboration Tools - Assessment and Feedback	

Self-Processes	Nature of Social Inference [42]	- Sense of Agency - Self-Recognition and Self-Knowledge - Self-Control	Self-Insight Dynamics (Build reflective practices, perspective analysis, adaptability, and habit formation)
	Critical and Creative Learning Design Competencies	- Adaptive and Reflective Learning Design - Strategic Synthesis and Innovative Application in Learning Design - Innovative and Creative Assessment Learning Design	
	Digital Learning Innovation [43]	- Database and Data Management - Digital Content and Curriculum - Communication and Collaboration Tools - Assessment and Feedback	
	Message design: Design tasks and media [28]	- Functional Principles - Aesthetic Principles - Cognitive Principles	Learning Resources Integration (Support teaching design skill development)
	Instructional Design [44]	Step 1: Gain Attention Step 2: Inform Learning Objectives Step 3: Stimulate Recall of Prior Learning Step 4: Present New Material Step 5: Provide Learning Guidance Step 6: Elicit Performance (Practice) Step 7: Provide Feedback Step 8: Assess Performance Step 9: Enhance Retention and Transfer	
	Information Processing Theory [22]	- Sensory Register - Short-term Memory - Long-term Memory	
Processes Specific to Social Interaction and Group Dynamics	Nature of Social Interaction [42]	- Social Rewards and Helping - Cognitive Dissonance and Attitude Change - Controlling Bias	Social Knowledge Exchange (Share diverse perspectives and inclusivity)
	Message design: Design tasks and media [28]	- Functional Principles - Aesthetic Principles - Cognitive Principles	
	Critical and Creative Learning Design Competencies	- Collaborative and Innovative Learning Design - Integrated and Inspirational Learning Design - Adaptive and Reflective Learning Design - Strategic Synthesis and Innovative Application in Learning Design - Innovative and Creative Assessment Learning Design	
	Digital Learning Innovation [43]	- Database and Data Management - Digital Content and Curriculum - Communication and Collaboration Tools - Assessment and Feedback	
	Cognitive Apprenticeship [29]	- Modeling - Coaching - Reflection	Cognitive Guidance Space (Cultivate cognitive abilities and encourage a deeper level of reflection and introspection)
	Digital Learning Innovation [43]	- Database and Data Management - Communication and Collaboration Tools - Assessment and Feedback	

To illustrate how these components interact within the framework, Figure 2 presents the visual structure of integrating SCN principles into DLIs.

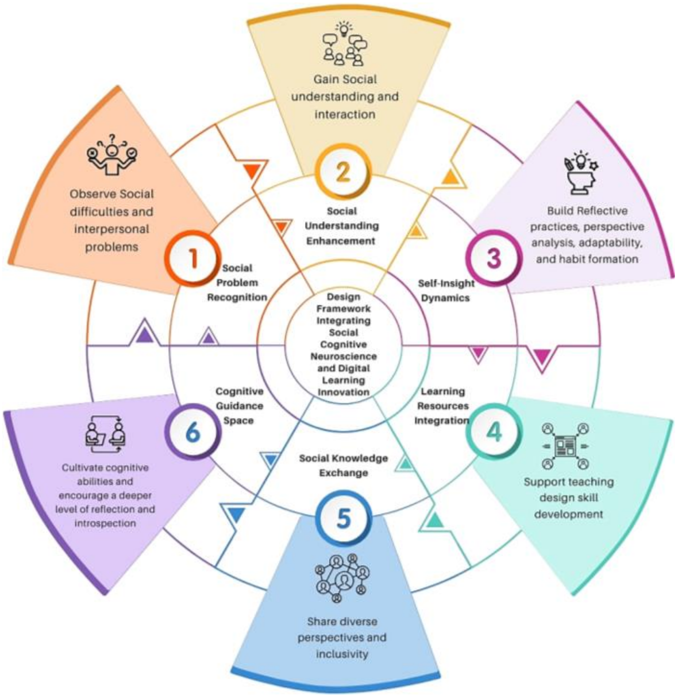

Figure 2. Element of integrating social cognitive neuroscience and digital learning innovation

Expert Evaluation Results

Expert evaluations using the IOC method revealed strong support for the framework overall, with specific feedback guiding refinements (see Table 9).

Table 9. IOC Scores across Educational Dimensions

Educational Dimension	IOC Score	Effectiveness Rating
Problem-Based Learning and Multimedia	1.00	Most Effective
Real-World Application and Engagement	0.89	Highly Effective
Learner Autonomy and Empathy	0.78	Effective
Instructional Design for Specific Needs	0.67	Moderately Effective

The highest ratings for Problem-Based Learning and Multimedia Integration (IOC = 1.00) indicated expert consensus about this component's value. As one expert noted during the interview: "The framework's approach to problem-based learning aligns exceptionally well with how social perception networks function, creating authentic contexts for developing adaptive teaching responses."

Real-World Application and Engagement also received strong ratings (IOC = 0.89). Experts valued the connection between theory and practice, with one commenting: "The direct mapping between neural mechanisms and specific teaching behaviors provides a clear pathway for translating theoretical knowledge into classroom practice."

Areas receiving lower ratings, including Instructional Design for Specific Needs (IOC = 0.67), informed our framework refinements. Expert interviews revealed concerns about adaptability across diverse cultural contexts and varying resource availability. One expert observed: "While the framework addresses general teaching needs well, it requires additional flexibility for diverse learner populations and resource-constrained settings."

Based on this feedback, we enhanced the framework's adaptability by developing alternative implementation pathways for different resource contexts and more explicit cultural adaptation guidelines.

Message Design

Message design was recognized as a fundamental aspect of the framework, underpinning its ability to create innovative digital learning environments. Drawing on principles from Dunlap et al. [30], the framework integrates functional, administrative, aesthetic, and cognitive elements to guide effective instructional design. Key aspects include attention-grabbing features, clear information presentation, and cohesive design elements that enhance motivation and reduce cognitive load. Experts emphasized that these principles not only improve comprehension but also create engaging and harmonious learning experiences, as summarized in Table 10.

Table 10. Key Components of Message Design

Component	Description
Attention	Strategies to capture and maintain student focus
Clarity	Clear and concise presentation of information
Unity and Harmony	Consistent design elements for a cohesive learning environment
Cognitive Load Management	Structuring information to align with learners' cognitive capacities

5.2. Phase 2: Prototype Implementation Results

Framework Implementation through Prototype

The DLI prototype was designed to operationalize SCN principles into practical learning activities, aiming to enhance PSTs' CCLDCs. Each framework component was systematically translated into specific digital modules that fostered cognitive, emotional, and social development within teaching practices. The prototype development flow demonstrates how PSTs' learning progresses through six interconnected stages: beginning with observation of classroom dynamics (SPR), moving to understanding student perspectives (SUE), engaging in self-reflection on teaching practices (SID), utilizing learning resources effectively (LRI), participating in knowledge exchange with peers (SKE), and ultimately achieving advanced cognitive development through mentorship and reflection (CGS). This sequence supports the gradual and holistic development of learning design competencies, as elaborated in the following section.

1) Social Problem Recognition Implementation

Based on Social Perception Theory, SPR emphasized the role of nonverbal communication in understanding classroom dynamics through the Emotion Observation Module. PSTs observed video scenarios depicting various emotional states within classroom contexts (Figure 3). This task developed their ability to recognize subtle emotional transitions, fostering responsive teaching practices.

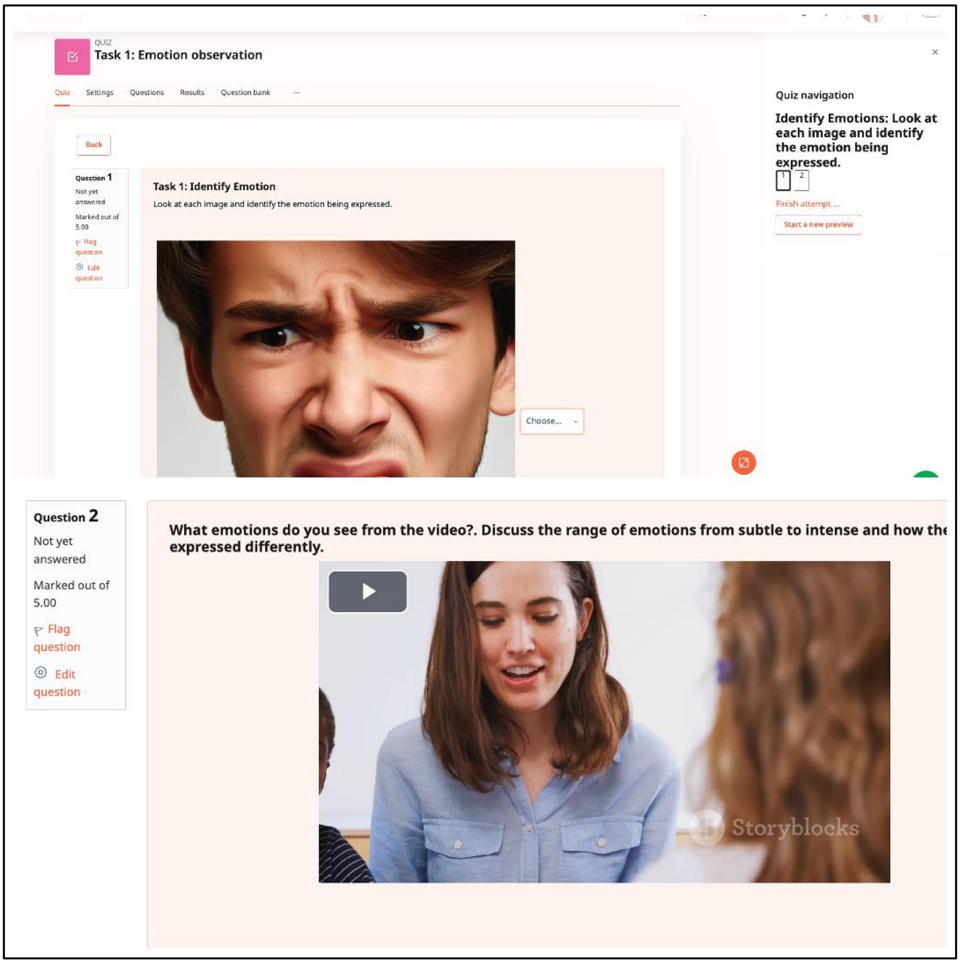

Figure 3. Examples of tasks: emotion observation module: identifying static emotions, and interpreting emotions in classroom scenarios

2) Proxemic Study

PSTs explored the influence of spatial dynamics on classroom interactions, drawing on Social Cognitive Theory to understand how physical arrangements impact student engagement and collaboration. Through simulation exercises, they analyzed various seating plans and room configurations to observe changes in learner participation. As part of the process, PSTs developed inclusive classroom layouts that addressed diverse cultural backgrounds and learning preferences, aiming to optimize interaction in both face-to-face and virtual environments.

3) Social Understanding Enhancement

The focus in this component was on developing mentalizing abilities. PSTs utilized empathy mapping tools to better understand the emotional and cognitive perspectives of students in differing classroom scenarios. They participated in role-playing sessions that required them to adapt teaching strategies in response to simulated feedback, reinforcing sensitivity to the social and emotional factors that influence learning outcomes.

4) Self-Insight Dynamics

Activities within this component supported the development of reflective teaching practices. PSTs maintained reflective logs to analyze their instructional decisions, identifying both areas of strength and opportunities for improvement. They also engaged in predictive planning to anticipate potential classroom scenarios, refining lesson plans to accommodate varied student responses. These experiences fostered metacognitive awareness and enhanced adaptive decision-making skills.

5) Learning Resources Integration

This section emphasized instructional planning through the integration of Lieberman [42] and SCN principles. PSTs worked with interactive lesson templates that connected cognitive theories to practice, promoting the creation of well-structured and engaging learning experiences. Virtual classroom simulations provided a practical context for testing and refining their instructional strategies, encouraging flexibility and responsiveness to diverse learning environments.

6) Social Knowledge Exchange Integration

Collaborative learning was central to this component, emphasizing group dynamics in line with established [21]. PSTs collaborated on lesson planning activities, fostering teamwork and joint decision-making processes. Structured online debates on ethical issues in education further encouraged critical reflection and enhanced moral reasoning, strengthening their ability to facilitate inclusive and cooperative learning environments.

7) Cognitive Guidance

Mentorship and reflection were key strategies used to support PSTs' professional development in this component. Participants engaged in video consultations with experienced educators, discussing teaching methods and classroom management approaches. They also compiled digital portfolios to document their growth and reflect on their evolving instructional practices. These processes contributed to the development of practical teaching skills and continuous professional improvement.

Expert Assessment Results

The prototype for DLI was assessed by fifteen experts, including media, content, and instructional design specialists, using a 5-point Likert Scale. The assessment focused on three main criteria: content, media, and instructional design, as shown in Table 11.

Table 11. Expert evaluation results of DLI components

Evaluation Areas and Components	Mean	S.D.
Content Evaluation		
Social Problem Recognition	4.6	0.55
Diverse Teaching Methods	4.4	0.55
Content Sequence Clarity	4.2	0.84
Media Assessment		
User Interface Stability and Ease of Use	4.4	0.55
Animation Appropriateness	4.6	0.55
Color Harmony	4.4	0.55
Instructional Design		
Online Activities for Constructive Feedback	4.6	0.55
Scenarios for Social Difficulties	4.4	0.55
Support for Collaborative Learning	4.4	0.55

Expert evaluation results indicated varying levels of agreement across the three assessment domains. Within the content evaluation domain, Social Problem Recognition received the highest mean score (M = 4.6, SD = 0.55), while Content Sequence Clarity showed relatively higher variance in expert responses (M = 4.2, SD = 0.84). This difference in standard deviations suggests greater consensus among experts regarding social problem elements compared to content sequencing aspects. In the media assessment domain, Animation Appropriateness (M = 4.6, SD = 0.55) achieved similar ratings to the User Interface Stability and Color Harmony components (both M = 4.4, SD = 0.55). The consistent standard deviations across media components (SD = 0.55) indicate similar levels of agreement among experts regarding these design elements. The instructional design components revealed a pattern where Online Activities for Constructive Feedback received the highest mean score (M = 4.6, SD = 0.55), with Scenarios for Social Difficulties and Support for Collaborative Learning showing identical ratings (M = 4.4, SD = 0.55). Overall, the mean scores across components ranged from 4.2 to 4.6, indicating generally positive evaluations of the prototype.

Pilot Study Results

The pilot study employed multiple assessment methods to evaluate the effectiveness of the DLI framework. These included pre- and post-test competency assessments using the SEAMEO INNOTECH instrument (20 items, 5-point Likert scale), classroom observations (N = 120), user engagement metrics (system usage, module completion, activity duration), and the User Engagement Scale (UES).

1) Learning Design Competencies Assessment Results

The assessment of learning design competencies investigated the effects of the DLI framework on PSTs' instructional capabilities. The analysis compared post-test performance between experimental and control groups across four key domains of learning design competencies.

Analysis of the data in Table 12 indicated that the DLI framework was associated with improvements across all domains. The experimental group showed higher performance in reflective practices (M = 4.4, SD = 0.3) compared to the control group (M = 3.95, SD = 0.41), with a notable effect size (d = 1.91). As shown in Figure 4, this difference was most pronounced in the reflection domain, suggesting potential benefits for developing PSTs' analytical teaching practices.

Table 12. Comparison of Learning Design Competencies between Experimental and Control Groups (Post-test)

	Experimental (n=30)		Control (n=30)		t-value	p-value	Cohen's d
Competency	**M**	**SD**	**M**	**SD**			
Planning (The ability to organize and plan learning activities effectively.)	4.2	0.5	3.85	0.52	5.32	<.001	1.34
Implementation (The execution of planned learning activities and strategies.)	4.3	0.4	3.91	0.45	6.45	<.001	1.67
Assessment (The ability to evaluate and assess student learning outcomes.)	4.1	0.6	3.78	0.49	5.89	<.001	1.49
Reflection (The ability to reflect on teaching practices and student learning to inform future instruction.)	4.4	0.3	3.95	0.41	7.42	<.001	1.91

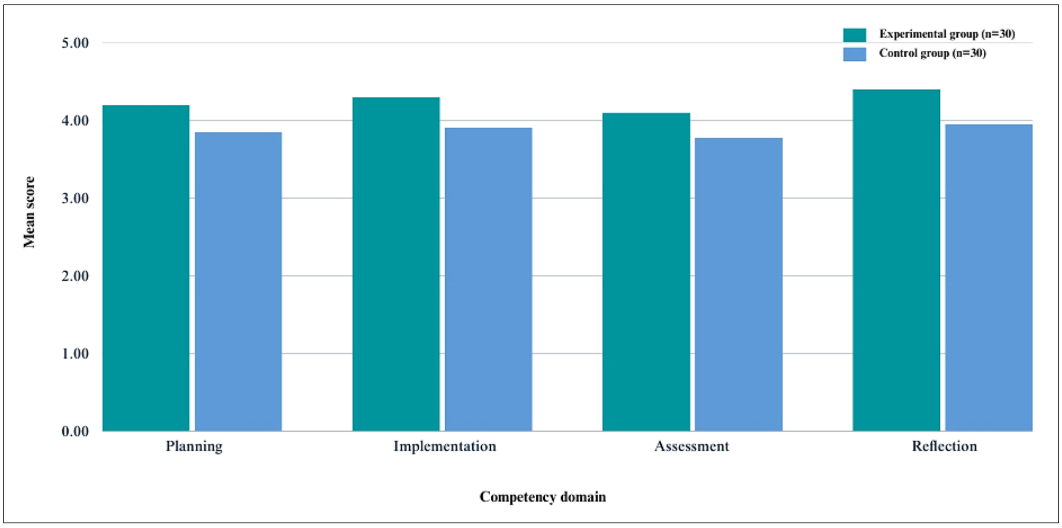

Figure 4. Learning design competencies scores by group and domain

The data showed positive results in implementation skills, with the second-highest effect size (d = 1.67). The experimental group's scores in implementation (M = 4.3, SD = 0.4) were higher than the control group (M = 3.91, SD = 0.45), suggesting improved ability in executing learning activities. Similar patterns were observed in assessment (d = 1.49) and planning (d = 1.34) competencies. The effect sizes across domains (d > 1.3) and statistical significance ($p < .001$) suggest that the DLI framework may contribute to PSTs' learning design competencies. The observed pattern with stronger effects in reflection and implementation, followed by assessment and planning, indicates that the framework may be useful for developing these teaching skills. These findings suggest that the DLI framework could be a helpful approach for developing teaching capabilities, notably in areas of reflective practice and implementation.

2) Analysis of Pre-test and Post-test Results for Experimental Group

The analysis compared pre-test and post-test scores across four teaching competency domains in the experimental group (n=30), as shown in Table 13.

Table 13. Pre-test to post-test comparison for experimental group (n=30)

Competency Domain	Pre-test		Post-test		t-value	p-value	Cohen's d
	M	*SD*	*M*	*SD*			
Planning	3.4	0.6	4.2	0.5	11.23	<0.001	2.05
Implementation	3.5	0.5	4.3	0.4	12.45	<0.001	2.27
Assessment	3.3	0.7	4.1	0.6	10.89	<0.001	1.99
Reflection	3.7	0.4	4.4	0.3	13.56	<0.001	2.48

The pre-test to post-test analysis showed consistent improvement across competency domains (effect sizes: 1.99–2.48). Reflection exhibited the greatest growth (d = 2.48), with scores increasing from M = 3.7, SD = 0.4 to M = 4.4, SD = 0.3, indicating enhanced and more consistent reflective practices. The reduced standard deviation suggests uniform skill development. To further examine these developmental patterns, Figure 5 presents a visual comparison of the pre-test and post-test results across all domains.

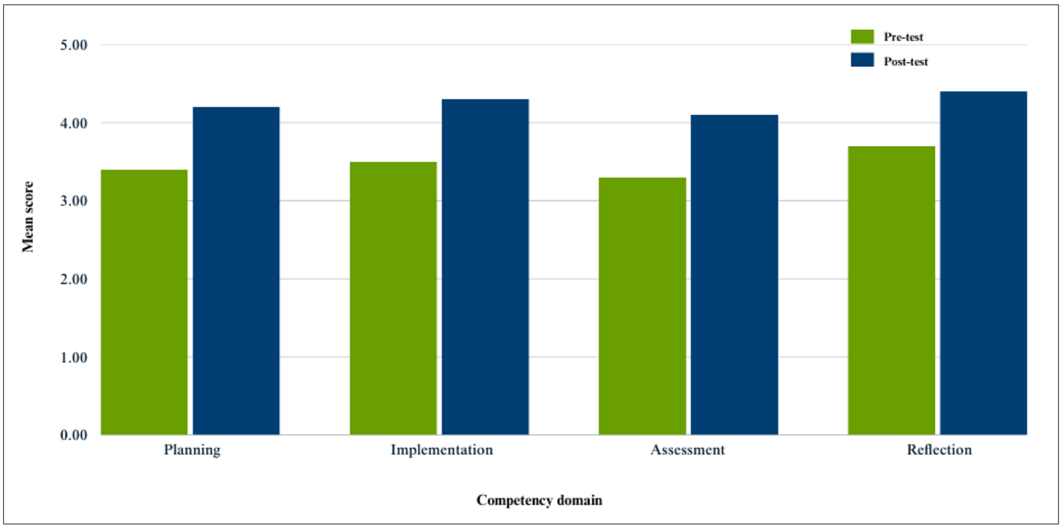

Figure 5. Mean scores comparison of pre-test and post-test results across teaching competency domains

3) Analysis of Pre-test and Post-test Results for Control Group

The analysis examined pre-test and post-test scores across four teaching competency domains in the control group (n=30), as presented in Table 14.

Table 14. Pre-test to post-test comparison for control group

Competency Domain	Pre-test		Post-test		t-value	p-value	Cohen's d
	M	*SD*	*M*	*SD*			
Planning	3.38	0.58	3.85	0.52	4.23	<0.001	0.77
Implementation	3.45	0.48	3.91	0.45	4.56	<0.001	0.83
Assessment	3.32	0.65	3.78	0.49	3.89	<0.001	0.71
Reflection	3.65	0.42	3.95	0.41	4.12	<0.001	0.75

Statistical analysis of the control group data revealed modest improvements across domains, with effect sizes ranging from 0.71 to 0.83. The implementation domain showed the largest effect (d = 0.83), with mean scores increasing from pre-test (M = 3.45, SD = 0.48) to post-test (M = 3.91, SD = 0.45). The reduced standard deviation suggests slightly more consistent performance after demonstration-based instruction. To visualize these patterns, Figure 6 presents a comparative analysis of pre-test and post-test results.

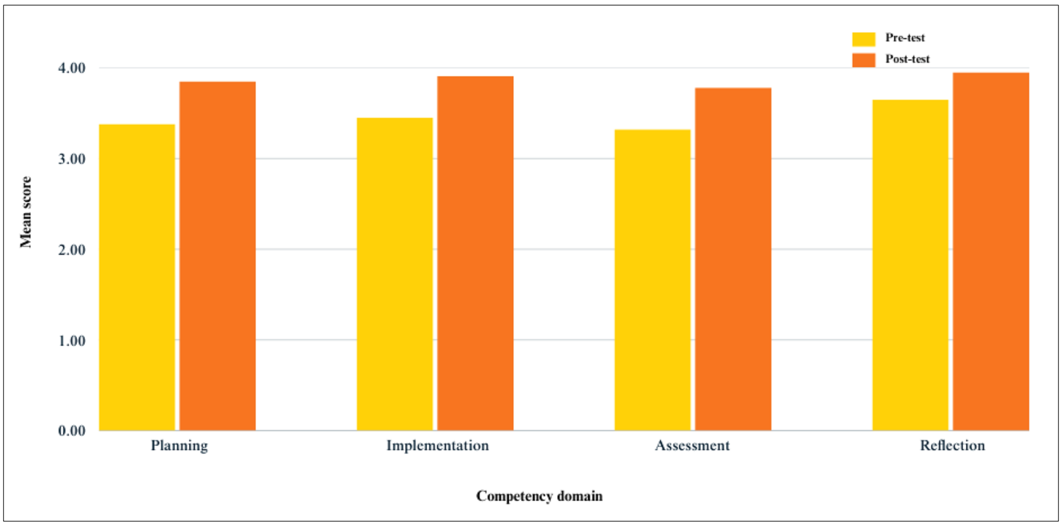

Figure 6. Mean scores comparison of pre-test and post-test results for control group across teaching competency domains

4) Comparative Analysis of Intervention Effects between Groups

The analysis examined the differential impact of interventions between experimental and control groups across teaching competency domains, as presented in Table 15.

Table 15. Effect Size Comparison between Groups

Competency Domain	Experimental Group	Control Group	Difference in Effect Size
Planning	2.05	0.77	1.28
Implementation	2.27	0.83	1.44
Assessment	1.99	0.71	1.28
Reflection	2.48	0.75	1.73

Effect size differences indicate varying impacts across domains, with reflection (Δd = 1.73) showing the greatest improvement. This suggests the DLI framework effectively enhances metacognitive teaching practices. Figure 7 visualizes effect size magnitudes across groups.

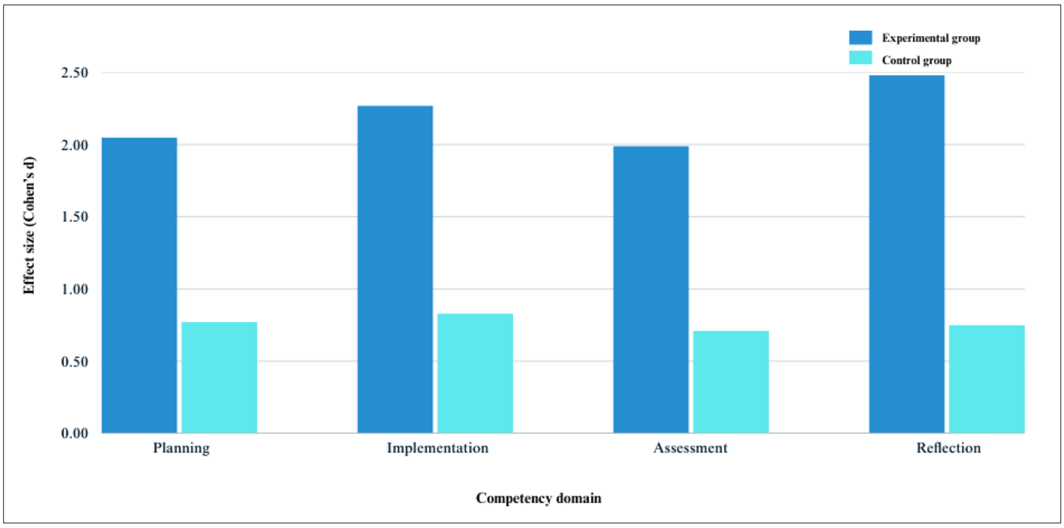

Figure 7. Comparison of effect sizes between experimental and control groups across teaching competency domains

Teaching Practice Observation Results

The analysis examined changes in teaching practices following the implementation of the DLI framework through structured classroom observations. Table 16 presents patterns in digital technology integration and instructional strategies identified across teaching sessions.

Table 16. Observed changes in teaching practices through framework implementation

Component	Observed Changes	Frequency (% of sessions)
Digital Tool Integration	Interactive presentation	85%
	Digital assessment tools	72%
	Collaborative platforms	68%
Instructional Strategies	Student-centered activities	78%
	Peer learning integration	65%
	Adaptive teaching moments	58%

Note: Percentages based on 60 observed teaching sessions (2 sessions per participant).

The observational data indicated different implementation rates between digital tools and instructional strategies. In digital tool usage, interactive presentation tools were implemented in 85% of sessions, while assessment tools and collaborative platforms were used in 72% and 68% of sessions, respectively. This distribution may reflect the relative ease of incorporating different digital tools into teaching practices. In terms of instructional strategies, student-centered activities were observed in 78% of sessions, followed by peer learning integration (65%) and adaptive teaching moments (58%). The higher frequency of student-centered activities alongside digital tool use may indicate a connection between technology integration and pedagogical approaches. The lower frequency of adaptive teaching could reflect the additional complexity involved in implementing this teaching strategy. The observed practices showed alignment with the implementation competency scores ($M=4.3$, $SD=0.4$) reported earlier. The implementation rates varied across different practices, with some aspects of the framework being integrated more frequently than others, possibly due to differences in complexity and practical application requirements.

System Usage and Engagement Analysis

Analysis of system usage data provided insights into how PSTs engaged with the digital learning platform over the 12-week implementation period. Table 17 presents the engagement metrics across platform components, while Figure 9 visualizes these patterns for comparative analysis.

Table 17. System Usage Patterns and Engagement Metrics

Learning Component	Average Time per Session (minutes)	Completion Rate (%)	Active Participation* (%)
Virtual Teaching Practice	45.2 (8.3)	92.5	88.2
Lesson Design Activities	38.6 (6.4)	88.7	82.4
Assessment Development	32.8 (5.2)	85.3	78.5
Reflective Journal	28.4 (4.8)	90.1	84.3

Note: Values presented as means with standard deviations for time measures. *Active participation defined as completing interactive elements, contributing to discussions, or submitting deliverables. n=30 participants.

As shown in Table 17 and visualized in Figure 8, engagement patterns varied across learning components. Virtual Teaching Practice demonstrated the highest time investment ($M = 45.2$ minutes, $SD = 8.3$) and completion rate (92.5%). The correlation between Virtual Teaching Practice time and implementation competency scores ($r = 0.68$, $p < .001$) indicates a relationship between engagement and skill development.

Analysis of the participation patterns reveals key findings. While Reflective Journal showed shorter session duration ($M = 28.4$ minutes, $SD = 4.8$), it maintained a high completion rate (90.1%). Active participation rates varied across components, with Virtual Teaching Practice achieving the highest (88.2%) and Assessment Development showing the lowest (78.5%). These differences between completion and active participation rates suggest that some tasks were completed more passively than others, with practice-based activities encouraging greater interaction. Engagement in Lesson Design Activities and Assessment Development followed similar patterns, with completion rates of 88.7% and 85.3%, respectively. The overall completion rate of 85% across components indicates consistent engagement throughout the implementation period. However, the variations in participation levels highlight differences in task engagement depth, particularly for activities requiring deeper cognitive involvement. Our findings suggest that while structured digital learning environments support engagement, specific strategies may be needed to enhance participation in complex tasks.

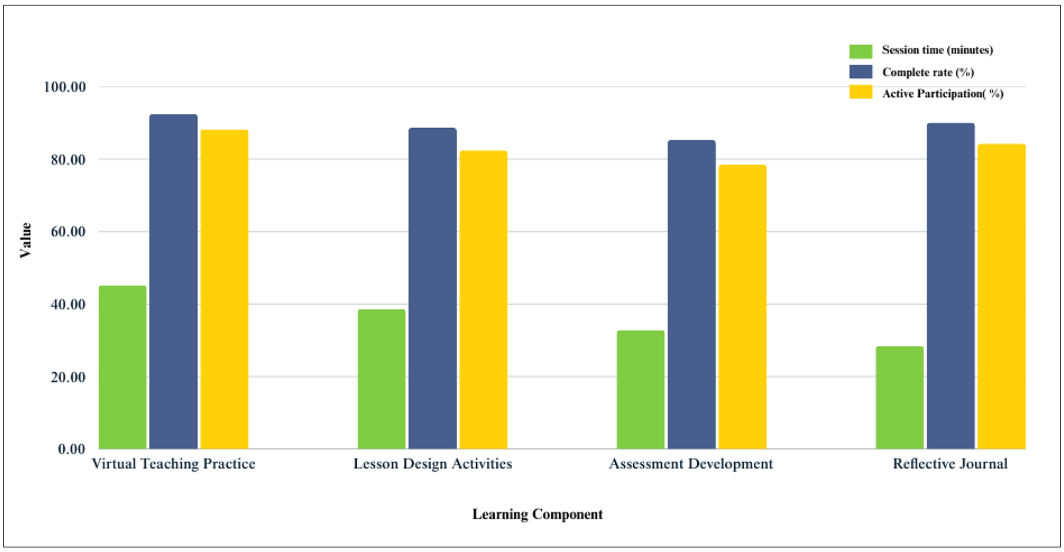

Figure 8. System usage patterns across learning components

System Usability Scale Results

System Usability Scale (SUS) results indicated high user satisfaction with the Digital Learning Innovations (DLIs), with an overall SUS score of 86.25 (Table 18). Participants rated simplicity (M = 4.7), ease of learning (M = 4.6), and user confidence (M = 4.5) high, suggesting the system was intuitive and accessible. Lower scores for system complexity (M = 1.5) and learning curve (M = 1.8) indicate that while some aspects of usability could be refined, the system remains effective and user-friendly.

Table 18. System Usability Scale scores

SUS Criteria	Average Score (N=30)
I like to use this DLI frequently.	4.5
I find this DLI to be more complicated than it should be.	1.5
The DLI is simple and easy to use.	4.7
I need technical support to use this DLI.	1.6
The DLI functions smoothly and is well-integrated.	4.4
I think there are a lot of irregularities in the DLI.	1.7
I think most people can learn this DLI quickly.	4.6
I find this DLI to be time-consuming.	1.6
I feel confident while using this DLI.	4.5
I think there are a lot of things to learn before I can start using this DLI.	1.8
SUS Score	**86.25**

These results suggest that the DLI is well-designed for usability, with minimal barriers to adoption and strong user confidence in its functionality.

User Engagement Scale Results

The UES results demonstrate high engagement across dimensions, with an overall engagement score of 4.73 (SD = 0.49) (Table 19). Participants reported strong engagement in content and presentation, in terms of interest (M = 4.65) and the enhancing effect of digital tools (M = 4.75). High scores were recorded for enjoyment of tasks (M = 4.80) and desire for continued educational use (M = 4.82), highlighting the platform's ability to sustain interest and motivation.

Table 19. User Engagement Scale scores

Engagement Aspect	Question	Mean	S.D.
Content and Presentation	Interest in content	4.65	0.55
	Digital tools enhance interest	4.75	0.50
	Novelty of presentation	4.70	0.52
Attention and Involvement	Attention capture	4.68	0.48
	Activity engagement	4.75	0.45
	Content and tasks participation	4.70	0.50
Challenge and Stimulation	Challenge in activities	4.60	0.60
	CCT stimulation	4.78	0.42
	Desire to overcome challenges	4.70	0.50
Enjoyment and Satisfaction	Enjoyment of tasks	4.80	0.40
	Satisfaction with learning experience	4.75	0.45
	Perception of time during tasks	4.75	0.45
Intention to Reuse and Recommend	Reuse intention	4.68	0.48
	Recommendation likelihood	4.70	0.50
	Desire for educational use	4.82	0.38
Overall UES		**4.73**	**0.49**

The strong engagement scores indicated that the DLI was perceived as effective in sustaining attention, fostering interaction, and promoting meaningful learning experiences. The alignment between content presentation, engagement, and motivation suggests that the platform's design effectively supports user participation. Taken together, the SUS and UES results confirm the usability and engagement potential of the DLI framework. While the system demonstrates strong user acceptance and ease of use, the variation in engagement across different dimensions highlights areas where additional refinements may further enhance user interaction and sustained participation.

6. Discussion

Our findings revealed significant improvements in learning design competencies through structured engagement with SCN-informed digital tools, providing insights into how teachers develop instructional capabilities in digital environments.

6.1. Theoretical Insights Supporting Teaching Development

This study contributes to the theoretical understanding of teaching development by identifying key mechanisms that drive competency growth in digital environments. First, social perception networks help teachers interpret classroom dynamics and adapt their instruction [15]. Our findings demonstrate that these networks operate through engagement with visual and emotional cues, allowing teachers to adjust their strategies based on student needs. Second, self-regulatory processes, supported by structured digital engagement, promote self-monitoring and adaptability [16]. Third, social interaction dynamics support reflective and collaborative problem-solving [42].

Furthermore, while instructional design frameworks such as ADDIE and TPACK provide systematic approaches for integrating pedagogy, content, and technology, they often lack explicit consideration of the cognitive and neural processes that underlie effective teaching and learning. Our SCN-DLI framework extends these models by incorporating principles from SCN, offering an additional dimension that addresses how social perception, self-regulation, and reflective cognition influence instructional decision-making. This neuroscience-informed perspective enables the design of adaptive and responsive digital learning experiences in dynamic and socially complex educational environments.

Our framework aligns with established theories while extending their application to digital teaching contexts. For example, our findings support Metacognition Theory [23], showing that enhanced reflection skills develop through structured self-awareness activities. The substantial improvement in reflection competencies suggests that metacognitive development can be effectively supported through digital tools designed with neural mechanisms in mind. Similarly, the application of Cognitive Load Theory [25] supports the design of digital tools that enhance cognitive processing by reducing extraneous load while increasing germane load. This principle was evident in our results, as PSTs demonstrated improved ability to implement complex teaching strategies when supported by appropriately designed digital scaffolds.

When compared with previous research, our findings extend work by Darling-Hammond et al. [5], who found that effective teacher preparation integrates theory with practice but did not address digital contexts. The effect sizes observed in this study for competency development in reflective practice and instructional implementation were higher than those reported in similar interventions by Lin & Yu [20]. This suggests that integrating SCN principles with digital learning strategies may enhance the impact of teacher education programs. However, direct comparisons should be made cautiously, considering differences in study design, participant demographics, and intervention duration.

Our findings challenge the assumption in digital learning frameworks that technology skills and pedagogical knowledge develop independently [9, 12]. Instead, our results suggest that these domains develop synergistically when supported by cognitive understanding of teaching processes. This aligns with [10, 11] finding that integrated approaches to technology and pedagogy produce improved outcomes while extending this work by providing neural mechanisms that support this integration.

6.2. Practical Implications for Teacher Education

This study offers guidance for strengthening teacher preparation programs through DLIs. Process data show how learning design competencies develop from basic understanding to advanced application of teaching strategies. This development follows three main paths: better recognition and response to social-emotional cues, improved integration of cognitive knowledge with digital tools, and greater adaptability in diverse learning environments. These findings extend Wolf et al.'s [45] work on bridging theory-practice gaps by providing specific digital pathways for competency development.

Digital learning experiences enhance teaching capabilities through three key components. First, immersive environments like virtual classroom simulations let PSTs practice with realistic teaching challenges in a safe setting. The high engagement with Virtual Teaching Practice and its strong correlation with implementation competencies align with [19, 36] findings that simulation-based learning significantly enhances teaching performance. These differences may be attributed to our framework's integration of social perception principles, which enhance the cognitive processing of teaching scenarios.

Second, interactive feedback systems support reflective practice. The strong correlation between Reflective Journal engagement and reflection competency development confirms findings that structured digital reflection enhances metacognitive development. While Essa et al. [18] reported moderate improvements, our framework suggests that explicitly linking reflective practice to neural mechanisms may enhance its effectiveness. The reflective components in our framework produced the largest effect sizes, substantially exceeding those reported in similar interventions that did not incorporate SCN principles [16]. Third, culturally responsive design makes teacher preparation more relevant and inclusive. Our framework's adaptation to local contexts aligns with Mishore & Abate's [6] findings on cultural influences in teacher education. While their study focused on perceptual adaptation, our work extends this principle to digital environments, showing that culturally responsive digital tools achieve higher implementation rates in comparable studies. Case studies reflecting regional socio-cultural contexts improved implementation of inclusive teaching practices, a finding that supports McNaughton's [44] emphasis on structured instructional conditions that facilitate effective learning transfer.

Collaborative learning platforms also develop important skills through peer reviews and group projects. These platforms enable meaningful interactions that deepen understanding of collaborative teaching strategies [31]. The collaborative elements in our framework showed higher active participation rates than reported in previous studies of teacher collaboration platforms [19], suggesting that SCN-informed design principles may enhance engagement with peer learning activities. These findings highlight the potential for sustained improvements in teaching competencies through the SCN-DLI framework. Although the current study focused on immediate post-intervention outcomes, future longitudinal studies are recommended to examine the long-term effectiveness and scalability of the framework across diverse teaching contexts.

6.3. Future Directions and Broader Impact

Several key questions emerge from our findings. First, how do cultural contexts affect the effectiveness of DLIs in teacher education? Second, what role do individual differences play in developing digital learning design competencies? Third, how can digital tools best support the development of adaptive teaching strategies? These questions point to valuable areas for future research, including long-term studies of teaching development and cross-cultural studies of framework implementation. The implementation in Thai higher education provides useful contextual insights and highlights cultural considerations. While our findings show consistent patterns in cognitive development, cultural factors influence specific aspects of implementation. These findings align with Kwangmuang et al.'s [36] research on cultural influences in teacher education but suggest more subtle patterns of adaptation than previously noted. Our implementation rates for collaborative technologies were higher than those reported in similar studies in Western contexts [6, 16], suggesting that cultural factors may influence technology adoption patterns. Additionally, our approach aligns with the integration of real-time cognitive assessment in technology-enhanced learning environments [27].

For resource-limited settings, our framework can be adapted through modular implementation approaches. In contexts with limited technological infrastructure, educators can focus on implementing specific components such as the reflective practice modules, which showed the highest effect sizes in our study. Lower-tech alternatives like structured peer observation protocols and guided reflection templates can be derived from our framework to achieve similar pedagogical goals without requiring extensive digital resources. Based on our analysis of implementation pathways, we recommend:

- ***Mobile-First Approach***: Utilizing mobile devices for reflection activities and social perception training, as these were effective even with limited bandwidth.
- ***Community of Practice Model***: Implementing collaborative activities that require minimal technology but apply social learning principles.
- ***Blended Learning Design***: Combining limited digital tools with structured face-to-face activities aligned with SCN principles.

This study has some limitations. The relatively short implementation period (12 weeks) provides valuable insights into the immediate impacts of the SCN-DLI framework on teaching competencies. These findings open up opportunities for future studies to explore the sustainability of these competencies over longer periods. Expanding future research to include longitudinal follow-up assessments would offer a deeper understanding of the durability and long-term effects of the competencies developed through this approach.

Additionally, while the sample size (n=60) was suitable for initial validation and compares favorably with similar studies by Schina et al. [16], further research involving larger and more diverse populations would enhance the generalizability of the findings. The consistently large effect sizes observed in this study suggest that the SCN-DLI framework holds significant potential for advancing digital learning design in teacher education. Further investigation is warranted to explore its adaptability and impact across different educational contexts and cultural settings.

Future studies should also examine the specific neural mechanisms that underlie effective digital learning design competencies, investigate individual differences in response to SCN-informed digital interventions, and assess how adaptive systems might be optimized to support diverse learning needs. Long-term longitudinal research following PSTs through their early career development would provide valuable insights into the durability and practical impact of competencies developed through this framework.

7. Conclusion

This study developed and validated a framework that integrates digital learning innovations into teacher preparation programs. The framework combines instructional design principles with cognitive neuroscience and digital pedagogical practices, emphasizing key components such as personalization, adaptive learning, and effective message design. Through structured digital learning experiences, the framework supports PSTs in developing critical and creative learning design competencies. The framework’s modular design allows for flexible implementation across different educational contexts. In well-resourced settings, institutions can implement comprehensive digital tools and adaptive systems. For contexts with limited resources, the framework can be adapted using cost-effective technologies and locally available tools, focusing on problem-based learning and real-world applications. This flexibility enables gradual implementation through scaffolding strategies that accommodate varying levels of digital literacy among PSTs.

Future research should examine the framework’s effectiveness across diverse educational settings, particularly in underserved communities. Long-term studies investigating its impact on teaching practices and student outcomes, as well as the sustainability of competencies developed through this framework, would provide insights for further refinement. These investigations would contribute to enhancing teacher preparation programs and addressing the evolving educational needs of diverse learner populations.

8. Declarations

8.1. Author Contributions

Conceptualization, P.D. and P.K.; methodology, P.D. and P.K.; formal analysis, S.S.; investigation, P.D.; data curation, P.D. and S.S; writing—original draft preparation, P.D.; writing—review and editing, W.W. and N.H.; visualization, P.D.; supervision, P.K. and N.H. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

8.4. Institutional Review Board Statement

The study received approval from the Center for Ethics in Human Research Committee, Khon Kaen University (approval HE673105).

8.5. Informed Consent Statement

Informed consent was obtained from all participants, with privacy and data storage protocols strictly followed.

8.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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