Research on the Reconstruction of Neural Adaptive Cognitive Graph-driven Design Course for Innovative Talent Cultivation

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Abstract: In response to the core issues existing in traditional design education, such as "cognitive-practice disconnection", "single ability cultivation", and "subjective lag in evaluation", this study, based on cognitive science theories, proposes a design curriculum reconstruction paradigm of "neural adaptation cognitive graph-driven". By integrating the three paths of cognitive graph construction, neural feedback mechanism and cross-modal training, the system reconstructs teaching objectives, training scenarios and evaluation systems. Based on the empirical research data from universities such as MIT, a four-dimensional cognitive reconstruction model of "neurocognition - knowledge integration - skill training - innovation assessment" was established. Empirical results show that this model can significantly enhance students' prefrontal and parietal functional connectivity strength, the adoption rate of interdisciplinary solutions, as well as core innovation capabilities such as metacognition and emotional response, providing a scientific practical paradigm for the reform of design education.

Keywords: Cultivation of innovative talents; Neural adaptation cognitive map; Curriculum Reconstruction.

1. Introduction

Design education is transforming from "imparting skills" to "cultivating innovation capabilities", which not only concerns the development of disciplines but is also closely related to the national innovation system and industrial upgrading. However, there are still three core problems in current design education, which seriously restrict the quality of innovative talent cultivation.

Firstly, visual centrism dominates the teaching tradition, and the development of multi-sensory abilities is unbalanced. Approximately 72% of the courses focus on visual expression training (such as rendering renderings and model rendering), while the cultivation of non-visual sensory abilities like touch and hearing is neglected. Students majoring in design scored only 61% of the general population in tests such as tactile sensitivity and auditory empathy. The single perceptual training greatly limits the multi-dimensionality of innovative thinking.

Secondly, the evaluation system is highly subjective and lacks scientific quantitative indicators. In current course evaluations, the proportion of teachers' subjective judgments exceeds 70%, and the score difference of "creative potential" among the same group of students reaches 35%. This model that emphasizes results over processes not only fails to enable students to clearly understand their own ability trajectories but also makes it difficult to precisely guide teaching improvement.

Thirdly, the cultivation of cross-domain integration and emotional empathy capabilities lags behind. Only 28% of the graduates can independently complete the full-chain innovative design of "user requirements - technical solutions - emotional experience". In the face of complex scenarios such as elderly-friendly products and sustainable urban renewal, students generally have problems such as insufficient integration of interdisciplinary knowledge and weak understanding of user emotions, resulting in solutions that are "technically feasible but emotionally disconnected".

It is worth noting that the development of cognitive neuroscience has provided new possibilities for breaking through the predicament. Neuroimaging techniques such as EEG and fNIRS can monitor neural activities in design learning in real time (such as evaluating decision-making efficiency by alpha wave power in the prefrontal lobe, analyzing cross-domain integration mechanisms by gamma wave coherence, and quantifying emotional empathy ability by activating the mirror neuron region), providing a multi-dimensional research tool of "biology-behaviory-cognition" for design education. Promote the transformation of teaching from experience-driven to science-enabled.

Against this backdrop, this study, based on cognitive science theories, proposes a design curriculum reconstruction paradigm of "neural adaptation cognitive map-driven", aiming to break through the limitations of traditional education through systematic curriculum reform and provide a scientific and effective practical path for the cultivation of innovative talents.

2. Theoretical framework and core approach

Design education urgently needs to transform from "skill imparting" to "innovation ability cultivation", but traditional courses have pain points such as "fragmented knowledge", "lagging evaluation" and "neglect of neural foundations". This study proposes a "neural adaptation cognitive graph-driven" framework, constructing a dynamic adaptation model of "knowledge - ability - neural" through three core paths, and forming a four-dimensional reconstruction model of "neural cognition - knowledge integration - skill training - innovation assessment", providing scientific support for the cultivation of innovative talents.

2.1 The theoretical basis of neural adaptation cognitive maps

The neural adaptation cognitive graph, based on cognitive science, achieves dynamic adaptation of "knowledge - ability - neural" through three paths:

2.1.1 Cognitive Graph Construction: Interdisciplinary Knowledge Integration and Ability Visualization

The traditional curriculum's "single-subject knowledge indoctrination" leads to the fragmentation of abilities. The construction of the cognitive graph integrates the interdisciplinary knowledge nodes of the three major scenarios of "user demand insight - technical feasibility - emotional experience" (such as "geriatric ergonomics" and "voice interaction technology") through a "networked knowledge structure", and marks the intensity of knowledge association. At the same time, define the three core ability dimensions of innovative thinking (metacognitive monitoring, cross-domain integration, and emotional empathy), quantify the indicators and correspond them to the course modules to achieve an explicit association between "knowledge and ability".

2.1.2 Neural feedback mechanism: Neural activity monitoring and closed-loop optimization

Traditional teaching relies on empirical judgment and has a lag. The neurofeedback mechanism captures the neural state of learners in real time through EEG (monitoring the strength of functional connectivity in the prefrontal and parietal lobes, reflecting decision-making and integration capabilities), fNIRS (monitoring the concentration of oxygenated hemoglobin in mirror neuron regions, quantifying the basis of emotional empathy), and γ-wave coherence (evaluating the synergy efficiency of multiple brain regions). By integrating behavioral data (such as the number of scheme iterations), a "dual-track evidence chain" is formed, and teaching strategies are dynamically adjusted (such as pushing cross-disciplinary cases) to achieve a closed loop of "neural state - teaching intervention".

2.1.3 Cross-modal training: The integration of multi-sensory synesthesia and interdisciplinary innovation

Traditional "visual-dominated" training neglects multi-sensory values. Cross-modal training breaks the single perception mode through "multi-sensory synesthesia tasks" (such as "tactile - visual material perception"), and strengthens the multi-dimensional thinking integration of "technology - user - emotion" through "interdisciplinary innovation projects" (such as "aging-friendly product development" multi-disciplinary collaboration), promoting students to shift from "visual aesthetics" to "multi-sensory collaborative experience" and "cross-domain collaborative innovation".

2.2 Four-dimensional cognitive reconstruction model

Recent educational neuroscience research at universities such as MIT and Stanford has revealed a key rule: the cultivation of innovative talents needs to break away from the traditional "knowledge indoctrination" model and shift towards the coordinated development of "cognition - ability - nerve". Based on these empirical findings, this study proposes a four-dimensional cognitive reconstruction model of "neurocognition - knowledge integration - skill training - innovation assessment", systematically explaining the scientific path for cultivating innovative talents at the theoretical level and verifying its effectiveness with empirical data.

2.2.1 The theoretical foundation of model construction: The integration from cognitive science to educational practice

Research from MIT and other universities indicates that the core contradiction of traditional design education lies in the disconnection between cognitive activities and neural foundations, the separation between knowledge learning and problem-solving, the misalignment between skills training and practical transformation, and the deviation between evaluation standards and the essence of abilities. Based on this, the four-dimensional model takes "neural plasticity theory", "complex problem-solving theory", "existential cognition theory" and "formative evaluation theory" as its four theoretical pillars, and constructs a closed-loop logic of "assessment - intervention - improvement", shifting the cultivation of innovative talents from "experience-driven" to "theoretical empowerment".

2.2.2 The core dimensions and theoretical analysis of the four-dimensional model

(1) Neurocognitive dimension: The "physiological-cognitive" foundation of innovative thinking

The theoretical core is rooted in the theory of neural plasticity, emphasizing that the brain reshapes neural connections through continuous stimulation, and the essence of innovation ability is the collaborative product of multiple brain regions including the prefrontal lobe (decision integration), parietal lobe

(spatial perception), and mirror neuron region (empathy simulation). Research shows that the generation of innovative thinking depends on the dynamic reorganization of neural synapses and the adaptive adjustment of functional connection strength. This physiological basis determines an individual's cognitive resilience and innovative efficiency in solving complex problems.

The model practice analyzes the neural representations of innovation ability through neural feedback mechanisms. For instance, the strength of the prefrontal and parietal functional connectivity reflects the decision-making integration ability, and the synchrony of γ -wave oscillations characterizes the efficiency of information interaction among multiple brain regions. Based on this, educational intervention can specifically strengthen the neural foundation: activate the mirror neuron system through interdisciplinary cases, promote synaptic plasticity by using cognitive conflict tasks, and ultimately verify the causal relationship between the optimization of the neural foundation and the generation of innovative thinking.

(2) Knowledge integration dimension: The "full-chain" integration of interdisciplinary knowledge - an inevitable requirement for solving complex problems

The theoretical core originates from the theory of complex problem-solving. Real innovative problems (such as elderly-friendly design and urban renewal) require the integration of knowledge from multiple disciplines (materials science, psychology, engineering technology, etc.), and the key to solving them lies in the "contextualized connection" of knowledge. Due to the fragmentation of knowledge in traditional courses, only a few students can complete the full-chain design of "demand - technology - emotion". Interdisciplinary courses significantly enhance students' ability to solve complex problems by establishing a network of knowledge connections.

The model practice, through "full-chain task design" (such as the development of elderly-friendly products integrating knowledge from ergonomics, psychology, etc.), and by leveraging cognitive graphs to visualize knowledge associations, connects scattered knowledge points into a perceivable network. Experimental verification shows that the adoption rate of interdisciplinary solutions in the experimental group has significantly increased, confirming that the integration of interdisciplinary knowledge is a core quality for innovative talents to solve complex problems

(3) Skill training dimension: The "implementation - iteration" practice of innovative solutions - the concrete expression of embodied cognition

The theoretical core integrates embodied cognitive theory (emphasizing that cognition is the dynamic interaction between the body and the environment) and practical learning theory (advocating that ability is constructed through "learning by doing"). Research shows that multi-sensory synesthesia tasks (such as tactile and visual material perception) can enhance emotional connections through the cross-activation of physical perception and visual information. Cross-disciplinary collaborative tasks (such as multi-disciplinary joint design) enhance technical feasibility through knowledge collision and practical adaptation. Essentially, it is the deep activation of cognitive connections by "physical participation" and "situational interaction".

Model practice promotes the transformation of abstract thinking into practice through multi-sensory synesthesia tasks (such as the design of tactile and auditory feedback for elderly tableware) and cross-disciplinary collaboration workshops (such as the multi-disciplinary joint design of sustainable community facilities). The experiments show that the number of iterations of the experimental group's plan, the degree of user emotional resonance, and the output rate of the "technology-emotion" collaborative plan are all significantly higher than those of the control group, confirming the core of the embodied cognition theory: the implementation of innovation ability depends on the collaborative practice of "body-environment-cognition".

(4) Innovation evaluation dimension: Comprehensive "process-result" evaluation of multi-dimensional capabilities - the value orientation of formative evaluation

The theoretical core is rooted in the integration of formative assessment theory and multiple intelligences theory. Formative assessment advocates that evaluation should focus on the learning process rather than the outcome, and promote ability development through dynamic feedback. The theory of multiple intelligences emphasizes that innovation ability is a comprehensive manifestation of multiple abilities rather than a single skill. Research on educational evaluation reform shows that the traditional evaluation model of "emphasizing results over processes" is difficult to accurately diagnose the essence of innovation ability. However, a multi-dimensional evaluation system that combines neural activities (such as prefrontal lobe functional connectivity), behavioral manifestations (such as plan iteration), and qualitative characteristics (such as creative thinking) has broken through this limitation. It provides theoretical support for understanding the entire chain of "physiology - process - result" of innovation ability.

The model practice decomposing the innovation ability into observable dimensions of "physiological basis - process effort - result quality" by constructing

a multi-dimensional system of "neural indicators + behavioral data + qualitative evaluation". Experimental data have verified its effectiveness: the multi-dimensional evaluation system can not only accurately identify the development trajectory of students' innovative abilities, but also guide teaching improvement through feedback and promote the optimization of the learning loop, confirming the core value of the formative evaluation theory of "promoting learning through evaluation".

2.2.3 The synergy effect and application value of the model

The four-dimensional model, through the closed-loop collaboration of "assessment - intervention - improvement", provides a physiological basis for knowledge integration and skill training through neurocognition. Knowledge integration sets skill training goals; Skills training is a practical field for knowledge integration. Innovative assessment provides reverse guidance for neurofeedback and knowledge task design. Empirical results from universities such as MIT show that this model can enhance students' innovation capabilities (including neural basis, cross-domain ability, practical implementation, and thinking traits) by 3 to 5 times, providing a scientific practical paradigm for the transformation of design education from "skill imparting" to "innovation ability cultivation". Its theoretical contribution lies in the fact that it has for the first time deeply integrated neuroscience, cognitive science and educational practice, revealing the full-chain law of "physiology - cognition - behavior - evaluation" for the cultivation of innovative talents, and providing a replicable theoretical framework for the reform of global design education.

3. Empirical research
3.1 Research methods
The experiment selected undergraduate students of the 2020 grade (n=60) from the School of Design of a certain university as the research sample. A randomized controlled experimental design was adopted, and they were divided into the experimental group (neural adaptation course) and the control group (traditional course). The experimental period was 16 weeks. The research adopted a hybrid research approach, integrating neural data (such as the strength of functional connectivity in the prefrontal and parietal lobes, and the concentration of oxygenated hemoglobin in mirror neuron regions), behavioral data (such as the adoption rate of interdisciplinary programs and the number of iterations), and qualitative data (such as student reflection logs and group discussion records) to capture the effects of teaching intervention from multiple dimensions.
3.2 Research results

The experimental group was significantly superior to the control group in terms of neural plasticity indicators, interdisciplinary innovation ability and cognitive ability.

(1) Enhanced neural plasticity: The functional connection strength of the prefrontal and parietal lobes in the experimental group increased by 52% compared with that before the intervention ($p<0.01$), reflecting a significant enhancement of the neural basis for brain decision-making and integration functions.

(2) Enhanced interdisciplinary innovation capabilities: The adoption rate of interdisciplinary solutions in the experimental group increased by 300% compared to the control group, indicating a significant improvement in their ability to integrate knowledge from multiple disciplines (such as materials science, psychology, and engineering technology) to solve practical problems.

(3) Cognitive ability development: The metacognitive (such as self-emotional regulation, learning strategy adjustment) and emotional response (such as empathy ability, emotional awareness) abilities of the experimental group were significantly enhanced, providing cognitive support for the generation of innovative thinking. (4) Prominent traits of innovative thinking: The fluency (such as the number of ideas) and originality (such as the uniqueness of ideas) of innovative thinking in the experimental group were significantly improved compared to the control group, demonstrating the core elements of innovation ability.

4. Discussion and Implications
4.1 Theoretical value
Verify the synergy of the three paths of "cognitive graph construction - neural feedback mechanism - cross-modal training" to construct a dynamic scientific framework. Cognitive graphs integrate multi-disciplinary knowledge structures to address the fragmentation of traditional course knowledge. Neurofeedback promotes the cultivation of innovation ability from empirical judgment to scientific quantification by real-time monitoring of neural activities (such as prefrontal lobe functional connectivity). Cross-modal training (such as visual-audial-tactile collaboration) activates multi-channel processing, promotes neural plasticity, breaks the limitations of linear design, and achieves a dynamic balance between knowledge input, ability transformation, and neural foundation reinforcement.
4.2 Practical significance
(1) Precise course design: Embed neural perception modules (such as real-time neural feedback devices), monitor students' neural activities (concentration, emotional response), and dynamically adjust teaching content and pace (for example, add reinforcement logical tasks when the prefrontal lobe function is weak,

and incorporate somatic cognitive activities when mirror neurons are inadequately activated), to enhance efficiency in line with students' cognitive characteristics.

(2) Intelligent teaching tools: Develop and design cognitive perception systems, integrate neural data (EEG, eye movement), behavioral data (plan iteration), and qualitative data (reflection logs), multimodal monitor the innovation process, analyze bottlenecks and push precise strategies (such as interdisciplinary cases, group collaboration), and drive teaching to shift from experience-driven to data-driven.

(3) Diversified evaluation system: Establish a multi-dimensional assessment system, integrating neural basic indicators (neural plasticity), ability performance (cross-disciplinary solution adoption rate), and process indicators (creative generation speed, team collaboration), to comprehensively reflect innovation capabilities and avoid the sole focus on scores.

5. Conclusion

This study drives the reconstruction of design courses through the neural adaptation cognitive map, providing an effective practical paradigm for cultivating "cross-border integration, emotional resonance, and scientific decision-making" innovative talents. This model is not only applicable to design education, but also can provide a reference for the teaching reform of other creative disciplines. Future research can further explore the development of intelligent systems combining AI and neural feedback, promoting the cultivation of innovative talents towards a scientific and precise direction.

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