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RESEARCH ARTICLE

Prefrontal Cortex Activation in Elementary Students during Biomimicry-based Convergent Thinking

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ABSTRACT

This study explored prefrontal cortex (PFC) activation in elementary students during biomimicry-based convergent thinking using functional near-infrared spectroscopy (fNIRS). Sixteen sixth-grade students completed a task consisting of Exploration, Design, and Implementation phases while their hemodynamic responses were recorded. Each phase showed distinct neural activation patterns. The Exploration phase elicited significant activation in the left dorsolateral prefrontal cortex, reflecting intensive verbal working memory and information manipulation. During the Design phase, broader PFC activation was observed in the right dorsolateral and ventrolateral prefrontal cortices and the left frontal pole, indicating imagery-based creative synthesis, planning, and goal-directed multitasking. The Implementation phase mainly involved the right ventrolateral prefrontal cortex and left frontal pole, suggesting increased demands on cognitive flexibility, self-regulation, and error monitoring. Previous neurodevelopmental studies have reported that adolescents tend to demonstrate greater neural efficiency and more distributed network engagement during complex cognitive tasks. In contrast, the present findings suggest that elementary students rely more heavily on core PFC resources to manage cognitive load during biomimicry-based convergent thinking. These findings highlight the need for convergent education at this level to emphasize instructional scaffolding that reduces cognitive overload and supports the development of executive functions, particularly planning and monitoring.

Keywords: Convergent thinking, biomimicry, fNIRS, prefrontal cortex, elementary students, executive function

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Introduction

Modern society is characterized by rapid change and increasingly complex problems, making the cultivation of individuals capable of solving multifaceted future challenges an urgent educational task (Kim et al., 2020; Ramírez-Montoya et al., 2025).

In response to this demand, convergent education—which integrates knowledge from multiple disciplines within a single learning context—has been emphasized, particularly in elementary education (Woo & Yoo, 2013; Wu et al., 2024; Yim et al., 2024). Educational approaches such as STS education, focusing on the relationship among science, technology, and society (Choi & Chang, 2005; Chrysochou et al., 2025), and STEM/STEAM education, which incorporate engineering, mathematics, and even the humanities and arts into science learning (Chrysochou et al., 2025; Madden et al., 2013; Tran et al., 2021), have been increasingly implemented in elementary classrooms and textbooks.

Recently, attempts have been made to move beyond instructional formats and outcomes and to examine convergent education at the cognitive and neural levels. Representative studies include analyses of Leonardo da Vinci's convergent thinking process (Kwon et al., 2015) and neuroimaging studies investigating brain activation patterns during convergent thinking in high school students (Kwon et al., 2016; Oh et al., 2024). These studies suggest that convergent thinking is not a single, uniform process but unfolds across three phases—Exploration, Design, and Implementation—each involving distinct cognitive activities such as idea generation, planning, and outcome prediction (Kwon et al., 2016).

Despite these advances, existing research on convergent education exhibits two notable limitations. First, there is a lack of internal validation regarding how convergent education actually transforms students' thinking processes, as many studies have focused on peripheral factors such as motivation or instructional conditions rather than convergent thinking itself. Second, neurocognitive investigations of convergent thinking have been largely confined to specific age groups, particularly adolescents or high school students, leaving elementary students underrepresented in empirical research.

This limitation is especially significant given that elementary students are still developing core cognitive functions essential to convergent thinking, such as working memory manipulation, planning, and self-regulation. Instructional models and programs derived from studies of older students may therefore not adequately reflect the developmental characteristics of elementary learners. Accordingly, empirical investigation of convergent thinking in elementary students is necessary to refine existing convergent thinking models and adapt them to earlier developmental stages.

From a neurodevelopmental perspective, the prefrontal cortex (PFC) plays a central role in higher-order cognitive functions, including planning, judgment, monitoring, and evaluation, and exhibits pronounced developmental changes across childhood and adolescence (Blakemore, 2008; Burnett & Blakemore, 2009; Collins & Koechlin, 2012; Fuster, 2019; Miller & Cohen, 2001). Given these characteristics, examining PFC activation provides a meaningful basis for identifying developmental differences in convergent thinking processes.

Accordingly, the present study aimed to investigate the characteristics of convergent thinking in elementary students by analyzing phase-specific PFC activation during the Exploration, Design, and Implementation stages. Brain activation was measured using functional near-infrared spectroscopy (fNIRS), which can be safely and reliably applied to elementary students and allows assessment of PFC activation based on changes in blood oxygen concentration (Lee & Kwon, 2022; Park & Kwon, 2022).

Procedures and methods

Participants

The participants in this study were 16 sixth-grade students (10 boys, 6 girls) from an elementary school located in the central region. All participants were right-handed and had no history of mental illness. Their vision and literacy were sufficient to perform the tasks, and they were able to clearly report their state verbally during the experiment process. As all participants were minors, explanations along with data about the study were provided to them and their guardians, and voluntary consent for participation was obtained from both the participants and their guardians. This process was conducted after approval by the Institutional Review Board of Gongju National University of Education.

Task

The purpose of this study is to elucidate the brain activation and connectivity of the PFC during convergent thinking in elementary students. Therefore, the task presented to students during brain activation measurement must be able to actively induce convergent thinking in elementary students. Thus, this study utilized a part of the convergent thinking tasks used in relevant prior studies (Kwon, 2017; Kwon et al., 2016; Oh et al., 2024) as a task to induce convergent thinking in students.

This task consists of several sets that present real-life problems and induce the application of biomimicry, utilizing the characteristics of surrounding organisms, as a method to solve them. It follows three phases: 'Exploration' to identify the problem and search for relevant knowledge, 'Design' to devise a creative output to solve the problem, and 'Implementation' to produce and evaluate the output. Due to the limitations of the brain activation measurement method, the 'Implementation' phase is conducted by imagining the actual activity virtually. To clarify the cognitive processes elicited by each phase of the convergent thinking task, the definitions of each phase, corresponding thinking activities, and primary cognitive functions induced are summarized in Table 1.

Oh et al. (2024) selected the set in which each phase of 'Exploration', 'Design', and 'Implementation' was easiest among several sets and applied it to the study, which was 'Making a shock-absorbing box' (Fig. 1).

Table 1. Phases of the convergent thinking task and induced cognitive functions

Phase	Task Focus	Induced Cognitive Functions
Exploration	Identifying the problem and exploring relevant biological and engineering knowledge	Verbal working memory, information retrieval and manipulation, goal setting
Design	Generating and planning creative solutions by integrating biological principles and engineering ideas	Imagery-based working memory, cognitive flexibility, planning and executive control
Implementation	Virtually executing and evaluating the planned solution through mental simulation	Self-regulation, metacognitive monitoring, error detection and correction

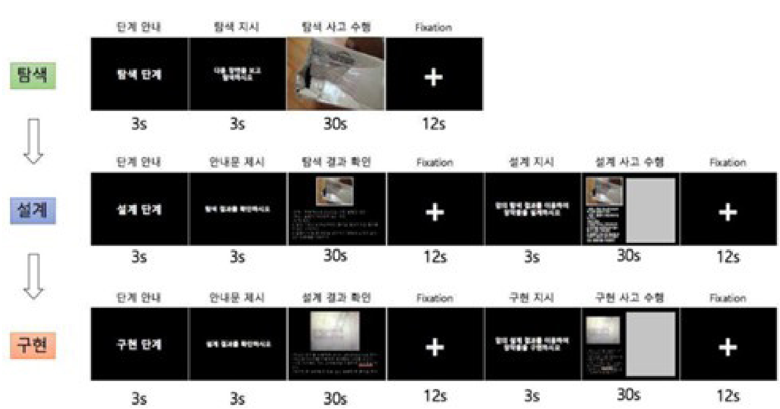

Fig. 1. Task for developing a shock-absorbing box (Oh et al., 2024)

Also, to facilitate the smooth induction of convergent thinking in participants, a preliminary task using cockleburs and Velcro was prepared for practice, identical to the prior study. This study intended to use this set as it is. For this purpose, validity was reviewed by three doctors in elementary science education and two incumbent elementary teachers with master's degrees and over 10 years of science education experience, and it was applied to this study after receiving opinions that it was suitable for use.

Data Collection

The data collection process of this study followed the procedures of Kwon et al. (2016), excluding parts related to brain activation measurement and analysis methods. Brain activation measurement procedures were conducted in accordance with the methods reported by Park et al. (2020).

Brain activity was measured using a portable functional near-infrared spectroscopy (fNIRS) device (OBELAB, Seoul, Korea). Unlike functional magnetic resonance imaging (fMRI), which requires participants to remain motionless in a confined scanner environment, fNIRS allows relatively natural task performance and is therefore more suitable for elementary students. In addition, fNIRS enables the measurement of prefrontal cortex activation based on changes in blood oxygen concentration, which is comparable to the hemodynamic signals assessed using fMRI. The device was temporarily fixed to the participant’s forehead to measure changes in oxy-hemoglobin concentration in four regions of the prefrontal cortex in each hemisphere: the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), frontal pole (FP), and orbitofrontal cortex (OFC). Data were collected at a sampling rate of 8.125 Hz across a total of 48 channels covering these regions.

To ensure sufficient engagement in convergent thinking during brain activation measurement, participants practiced the convergent thinking process through repeated performance of a pre-prepared preliminary task under the guidance of the researcher. Subsequently, each participant performed the main task individually in an independent space while viewing a laptop monitor and listening to the researcher’s instructions. Brain activation measurement equipment was worn prior to task execution, and task performance commenced after confirming signal stability.

During task performance, brain activation data were monitored and recorded in real time. Before the convergent thinking task, resting-state brain activation was recorded for approximately 2 minutes with the participant’s eyes closed. Participants then performed the convergent thinking task, during which the duration of each phase was automatically recorded. After approximately 20 minutes of task performance, the measurement equipment was removed, the participant’s condition was checked, and the collected data were inspected before terminating data acquisition. Following the experiment, participants were asked to write down their thoughts during task performance based on their recollection of each scene.

Data Analysis

The collected data were analyzed following the procedures described by Park et al. (2020). The raw fNIRS data were initially recorded as optical intensity signals, which include both task-related hemodynamic components and various sources of noise. To reduce physiological and instrumental noise, a band-pass filter and discrete cosine transform (DCT) were applied to the optical intensity data. Subsequently, the Modified Beer–Lambert Law (MBLL) was applied to convert the preprocessed optical intensity signals into changes in oxy-hemoglobin concentration for each channel and participant.

To determine the significance of brain activation, a general linear model (GLM) was constructed for the oxy-hemoglobin concentration changes by channel, using the Exploration, Design, and Implementation phases of convergent thinking and the resting period as conditions. The activation coefficient of the resting period was subtracted from the activation coefficient of each convergent thinking phase. A one-sample t-test was then performed on the resulting values for each channel and phase to examine activation significance. In addition, correlations between channels were calculated based on oxy-hemoglobin concentration changes to construct functional connectivity networks at both the channel and regional levels.

Results and Discussion

Brain Activation during the Exploration Phase of Convergent Thinking

As a result of analyzing brain activation performing the exploration phase, significant activation appeared in channel 34 (Figure 2). Channel 34 corresponds to the Left Dorsolateral Prefrontal Cortex (L-DLPFC), which is widely known as a core area responsible for cognitive control and Executive Function (Miller & Cohen, 2001; Fuster, 2019). It plays a pivotal role particularly in maintaining and actively manipulating information within Working Memory. This area is essential for the planning of strategies for problem-solving and the initiation of goal-directed behaviors, and is involved in high-level control of cognitive flexibility and attentional focus (Collins & Koechlin, 2012). In particular, the left DLPFC is highly associated with verbal information processing, performs thinking through inner articulation processes, and promotes divergent thinkingto generate new ideas.

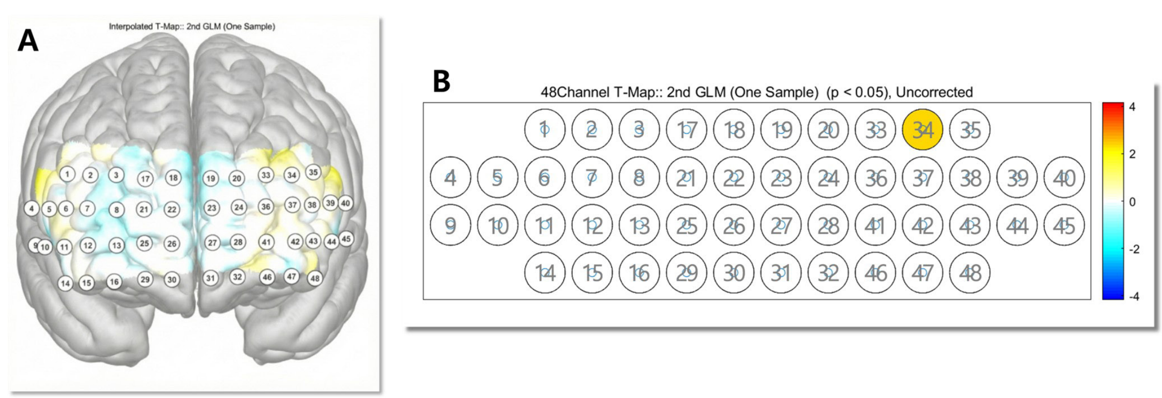

Fig. 2. Prefrontal cortex activation during the exploration phase (A: 3D model representation, B: channel-wise activation, $p < 0.05$)

The exploration phase is a process of identifying the problem situation, setting goals, and exploring related biological and engineering knowledge. The activation of the left DLPFC in this phase implies that active cognitive control beyond simple information reception is taking place. Since the left DLPFC is specialized in the manipulation of verbal working memory, it is interpreted that the learner is internally verbalizing the problem situation and actively maintaining and manipulating declarative knowledge retrieved from long-term memory within the working memory. In addition, since DLPFC activation is closely related to the function of strategic planning for problem-solving, this area plays a role in preparing for logical and step-by-step thinking for the subsequent design and implementation phases during the exploration phase.

The high activation of the left DLPFC in the exploration phase of convergent thinking proves that this phase is a process performed by integrating complex higher cognitive functions. This indicates that functions of generating various ideas and knowledge through divergent thinking for problem-solving and simultaneously objectively evaluating (mentalizing) whether the generated knowledge is suitable for problem-solving are accompanied. Also, the activity of the DLPFC reflects that the learner is allocating maximum cognitive effort in the process of setting goals for problem-solving and organizing knowledge necessary to achieve the goals. Therefore, the activation of the left DLPFC neurologically supports that the exploration phase is a process where divergent thinking, planning, verbal manipulation, and self-evaluation, which are core components of convergent thinking, are closely synchronized.

Brain Activation during the Design Phase of Convergent Thinking

As a result of analyzing brain activation performing the design phase, significant activation appeared in channels 6, 10, 24, and 28 (Fig. 3). The activation of the Right Dorsolateral Prefrontal Cortex (R-DLPFC, Ch 6), Right Ventrolateral Prefrontal Cortex (R-VLPFC, Ch 10), and Left Frontal Pole (L-FP, Ch 24, 28) in the design phase shows that higher-dimensional cognitive functions for problem-solving are actively mobilized. The DLPFC (Channel 6) generally plays a key role in maintaining and manipulating information in working memory, and the activation of the right DLPFC particularly supports that imagery-centered information manipulation was actively performed as presented (Murphy et al., 1998). The Left Frontal Pole (L-FP, Channels 24, 28) is an area involved in goal-directed multitasking and the organization of sub-goals (Collins & Koechlin, 2012). Since the design process is a complex process of devising the structure and production method of the output by integrating biological and engineering knowledge obtained in the exploration phase, the activation of the L-FP indicates that the learner is planning strategies to achieve the goal while simultaneously managing various criteria and information. Finally, the activation of the R-VLPFC (Channel 10) suggests that the learner is seeking diverse and original design alternatives by breaking away from existing cognitive constraints through a process of cognitive flexibility.

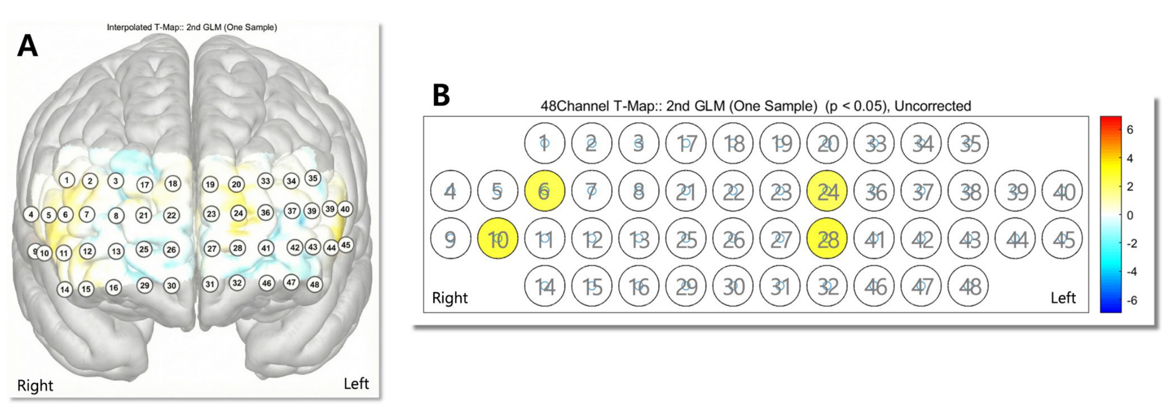

Fig. 3. Prefrontal cortex activation during the design phase (A: 3D model representation, B: channel-wise activation, $p < 0.05$)

The design phase is a core stage in the convergent thinking model where creative outputs are devised based on bio-engineering knowledge to solve problems. The simultaneous activation of the DLPFC, VLPFC, and FP means that this process is not simple knowledge retrieval but involves imagery-based creative synthesis and sophisticated planning. Specifically, the activation of the DLPFC actively edits and manipulates knowledge necessary for determining the structure, size, and material of the output within working memory, and the activation of the FP indicates that higher cognitive control organizing specific production and operation procedures (plans) to make these creative ideas feasibleis in action. The extensive activation of prefrontal areas implies that active cognitive effort was invested to generate new alternatives and realize them in a goal-directed manner, such as detecting errors during the process of devising and evaluating creative outputs and transmitting emotional evaluations to the reward circuit.

Brain Activation and Connectivity during the Implementation Phase

As a result of analyzing brain activation performing the implementation phase, significant activation appeared in channels 10 and 28 (Fig. 4). The Right Ventrolateral Prefrontal Cortex (R-VLPFC) (Channel 10) and Left Frontal Pole (L-FP) (Channel 28) activated in the implementation phase are prefrontal cortex areas responsible for high-level cognitive control and Executive Function (Miller & Cohen, 2001). The Frontal Pole (FP) is generally known as a core area involved in goal-directed thinking, multitasking, and the organization of sub-goals (Collins & Koechlin, 2012), and is particularly related to the function of monitoring and evaluating one's performance in the self-regulation process. Since this implementation task involves complex activities of producing the output based on the blueprint and devising evaluation criteria, the activation of the L-FP means that the learner was immersed in the process of integrally organizing and controlling the three sub-goals of production, operation, and evaluation. Also, the VLPFC is important for the flexibility of thought and the function of retrieving or clarifying information in working memory (Badre & Wagner, 2007). This suggests that the learner performed the role of exerting cognitive flexibility to immediately correct and seek alternatives when discrepancies or errors in the plan were discovered during the process of imagining the production and evaluating it according to the plan set in the design phase.

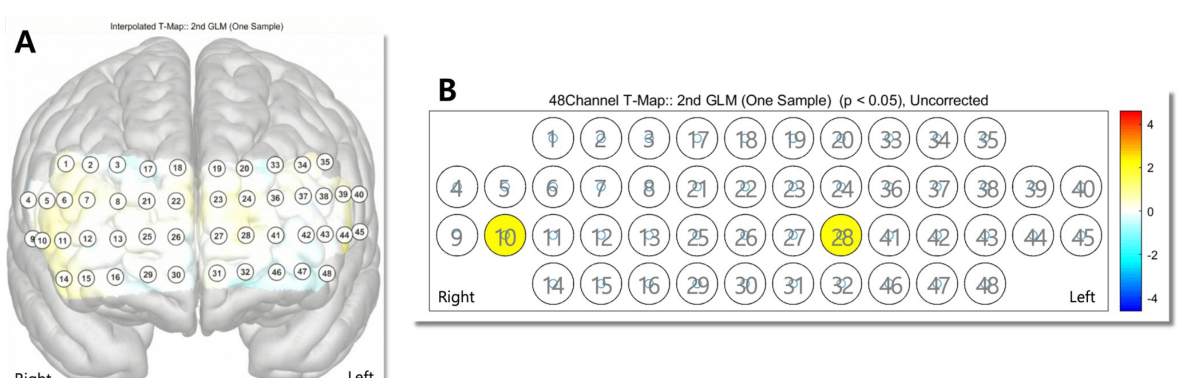

Fig. 4. Prefrontal cortex activation during the implementation phase (A: 3D model representation, B: channel-wise activation, p < 0.05)

In the convergent thinking model, the implementation phase is the stage of actually producing, operating, evaluating, and completing the creative output to solve the problem. The activation of the L-FP and R-VLPFC in this stage means that elementary learners performed a complex cognitive process of simultaneously proceeding with execution (imagining production and operation) and evaluation (checking results and modification). The activation of the FP indicates that the learner is systematically controlling the process of planning specific procedures necessary to complete the output, executing them (production in imagination), and evaluating them (devising and applying evaluation criteria). Particularly, since the implementation phase aims for final problem resolution, the flexible thinking action of the VLPFC shows that active self-regulation is taking place to quickly detect errors if the plan differs from expectations and apply new solutions through logical verbal clarification to move towards the goal. This coordination of prefrontal areas implies that the high level of cognitive concentration and evaluation ability required in the process of realizing the final output is being manifested.

The significant high activation in the Right Ventrolateral Prefrontal Cortex (R-VLPFC, Channel 10)and Left Frontal Pole (L-FP, Channel 28)during the implementation phase shows that this phase accompanied high-dimensional cognitive control and information manipulation in the process of producing and evaluating the designed output. In particular, the L-FP takes charge of goal-directed thinking that organizes and controls multiple sub-goals such as production, operation, and evaluation, and the activation of the R-VLPFC suggests that cognitive flexibility was exerted to actively seek alternatives when planning errors or discrepancies were discovered. This activation pattern of elementary students implies a concentration on core executive functions of plan maintenance and error evaluation.

Comprehensive examination of the brain activation results of the exploration, design, and implementation phases of elementary students' convergent thinking process reveals a continuous and intensive reliance on the executive function of the Prefrontal Cortex (PFC) areas, specifically the Dorsolateral Prefrontal Cortex (DLPFC), Ventrolateral Prefrontal Cortex (VLPFC), and Frontal Pole (FP). In the exploration phase, the left DLPFC and FP are activated, reflecting high cognitive effort to identify the problem situation based on language and retrieve and manipulate related knowledge. In the design phase, the process of synthesizing creative alternatives based on imagery and planning multiple goals becomes central with the activation of the right DLPFC, R-VLPFC, and L-FP. Finally, in the implementation phase, functional integration to simultaneously control production and evaluation and exert cognitive flexibility to solve problems is confirmed through the activity of the R-VLPFC and L-FP.

It should be noted that the Implementation phase in the present study was conducted as a virtual execution task based on imagination rather than actual physical production. As a result, the observed brain activation patterns primarily reflect executive control processes related to planning, monitoring, and evaluation, rather than sensorimotor processes associated with physical manipulation. Accordingly, activation in motor and sensory cortices was not expected and was not interpreted in the present analysis. This methodological constraint should be considered when interpreting the implementation-phase results, as the findings specifically represent cognitive execution and self-regulation processes rather than embodied action. Nevertheless, the imagined implementation approach allows for controlled examination of executive functions during task completion, which was the primary focus of this study.

Comprehensive examination of the brain activation results across the exploration, design, and implementation phases of convergent thinking in elementary students reveals a continuous and intensive reliance on executive functions mediated by the prefrontal cortex (PFC), particularly the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), and frontal pole (FP). Across all phases, elementary learners engaged core prefrontal mechanisms associated with working memory manipulation, planning, monitoring, and cognitive flexibility, indicating that convergent thinking at this developmental stage is strongly supported by focused executive control rather than distributed processing.

This PFC-centered activation pattern suggests that elementary students allocate substantial cognitive resources throughout the convergent thinking process and actively engage in metacognitive self-regulation to manage task demands. Given that higher-order cognitive functions are still developing during childhood, the present findings imply that elementary learners rely on fundamental executive strategies—such as problem recognition, basic planning, and error monitoring—when performing complex convergent tasks, potentially experiencing relatively high cognitive load.

Compared with previous neuroimaging studies on convergent thinking in high school students (Kwon et al., 2016; Oh et al., 2024), the present findings reveal both continuity and developmental differences. While convergent thinking across age groups consistently engages prefrontal cortex regions associated with executive functions, elementary students show a more concentrated reliance on core prefrontal areas. In contrast, high school students have been reported to recruit broader and more distributed neural networks extending beyond the prefrontal cortex. This difference suggests that convergent thinking in elementary students reflects an early, prefrontal-centered form of integration that precedes the more efficient and distributed neural organization observed in adolescents.

Conclusion and Educational Implications

This study aimed to elucidate the characteristics of prefrontal cortex activation in elementary students during biomimicry-based convergent thinking. Using functional near-infrared spectroscopy (fNIRS), changes in oxy-hemoglobin concentration were measured and analyzed across the Exploration, Design, and Implementation phases in 16 elementary school students. The findings demonstrate that elementary students engage phase-specific cognitive processes during convergent thinking, characterized by distinctive patterns of prefrontal cortex activation.

During the Exploration phase, prominent activation of the left dorsolateral prefrontal cortex (L-DLPFC) indicated intensive engagement of verbal working memory and cognitive control for problem recognition and knowledge manipulation. In the Design phase, activation of the right dorsolateral prefrontal cortex, right ventrolateral prefrontal cortex, and left frontal pole reflected imagery-based idea synthesis, planning, and cognitive flexibility. In the Implementation phase, activation of the ventrolateral prefrontal cortex and frontal pole suggested active metacognitive monitoring and self-regulation in coordinating planning, evaluation, and error correction.

Taken together, these results indicate that convergent thinking in elementary students is supported by a prefrontal-centered activation pattern, with substantial investment of executive functions and cognitive resources throughout the entire process. Within the defined methodological scope of this study, the findings suggest that elementary learners rely primarily on core executive strategies such as problem recognition, planning, monitoring, and evaluation, reflecting developmental characteristics of an executive system that is still undergoing maturation.

Based on these findings, several educational implications can be drawn. First, convergent education programs for elementary students require instructional scaffolding to reduce cognitive overload. Given the intensive engagement of prefrontal executive functions observed in this study, instructional strategies that structure information by phases and provide visual supports may help alleviate working memory demands.

Second, educational interventions aimed at strengthening executive functions—particularly planning and monitoring—are essential for enhancing convergent thinking in elementary students. The observed involvement of the frontal pole and ventrolateral prefrontal cortex underscores the importance of explicitly guiding students in goal setting, idea evaluation, and error correction during convergent learning activities.

Finally, the development of differentiated convergent curricula that reflect developmental differences in cognitive and neural maturation across school levels is warranted. At the elementary level, educational emphasis should be placed on verbal exploration, basic design planning, and self-evaluation—core functions of the prefrontal cortex—rather than on complex and fully integrated output production. Such experiences may provide a foundation for the development of more advanced convergent thinking supported by increasingly distributed neural networks in later stages of development.

Conflicts of Interest

The author(s) declared no conflicts of interest.

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