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RESEARCH ARTICLE

An Analysis of High School Students' Brain Activation During a Metaverse-based Biological Classification Activity

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ABSTRACT

This study aims to analyze the brain activity of high school students during a metaverse-based biological classification activity using functional Near Infrared Spectroscopy (fNIRS). For this study, we developed a biological classification inquiry activity by modifying a metaverse environment featuring a tidal pool and coastal dune, each populated with seven species of animals and plants. This activity was compared with a video lecture covering the same content. Brain activity analysis showed a significant increase in activation in the left orbitofrontal cortex (OFC), right ventrolateral prefrontal cortex (VLPFC), bilateral dorsolateral prefrontal cortex (DLPFC), and frontal pole cortex (FP) during the metaverse-based biological classification activity compared to the video lecture. When analyzing the sub-stages of the metaverse-based biological classification activity, there was a noticeable decrease in activation in the left VLPFC and right FP during the planning stage. Furthermore, group activities resulted in more channels being activated in the bilateral DLPFC compared to individual activities. These results indicate that metaverse-based biological classification activities more effectively stimulate motivation and goal-directed thinking, as well as the cognitive processes necessary for devising classification criteria.

Keywords : Metaverse, biological classification, high school, brain activation, prefrontal cortex, fNIRS

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Introduction

The increase in online activities triggered by the pandemic disease has led to the widespread use and user growth of the metaverse across various fields, including education (Yfantis & Ntalianis, 2022). The metaverse refers to a 3D virtual world that enables social, economic, and cultural activities that occur in the real world by substituting physical space (Wang et al., 2022). The metaverse has the potential to enhance interest and immersion in learning through experiences that are unattainable due to real-world limitations, as well as through interactions between instructors, learners, and learning content (Lim et al., 2023). This feature can serve as a viable alternative to experiential learning activities such as experiments or field trips, which have limitations in practical educational settings (Kuznetcova et al., 2019). Specifically, biology education can benefit from combining field activities, which can significantly increase interest and learning effectiveness (Ayotte et al., 2017; Meighan & Rubenstin, 2018). However, due to safety concerns and the challenges of preparation and execution, conducting field activities in biology classes is highly restricted, making the metaverse emerges as a viable alternative (Dwivedi et al., 2022; Kuznetcova et al., 2019).

In biology education, content that is closely linked to field activities often begins with the observation and classification of biological species (Oh et al., 2016). Classification involves observing various objects and identifying commonalities and differences to establish a hierarchical order, which is a generalization process (Kwon et al., 2003). Classification is fundamental to the generation of scientific knowledge (NRC, 2012) and plays a critical role in developing inquiry skills as part of problem-solving in scientific inquiry activities (Klauer, 2002). Despite its importance, actual educational settings often resort to lecture-based teaching focused on memorizing the classification knowledge presented in textbooks due to the challenges of conducting field activities (Cheong et al., 2016). Classification systems vary and change with time and context, and taxonomists may have different criteria for classification (Campbell et al., 2019). Since knowledge is constructed by individuals themselves, it is necessary to design activities that increase students' interest and provide diverse experiences rather than merely transmitting structured knowledge (Kim & Kim, 2018). Hence, it is crucial for students to experience the process of finding biologically valid classification criteria and grouping closely related organisms themselves, rather than relying on traditional knowledge transmission methods (Kwon & Lee, 2010).

Researches on programs for learning biological classification include those utilizing school gardens or supermarket organisms (Kim & Kim, 2018; Oh et al., 2016), programs using photographs or virtual organisms (Lim, 2019; Lee, 2010; Lee, 2012), and programs using the metaverse (Byeon, 2022; Byeon & Kwon, 2023). However, there have been studies on programs designed to learn biological classification, most have indirectly assessed effectiveness through the analysis of behaviorally expressed outcomes in paper-and-pencil tests, questionnaires, or interviews (Kwon & Lee, 2010). However, cognitive processes for solving specific problems, including classification, are evoked by brain functions, and learning processes aimed at cognitive changes necessitate changes in the brain (Bush, 2006). Therefore, observing and measuring brain activity can provide a more comprehensive explanation of cognitive activities during the learning process and allow for effective educational application based on this information (Byeon & Kwon, 2020; Kwon & Lee, 2010; Lee et al., 2012).

Studies analyzing brain activation during metaverse use, such as Park et al. (2023) and Kim et al. (2024), have argued that the autonomy provided by the metaverse may lead to impairments in goal-directed thinking. However, these studies also suggest that if an environment conducive to maintaining attention is provided, the metaverse can serve as a valuable tool for educational activities that promote free observation and exploration by learners. Nevertheless, neuroscientific research assessing the efficacy of metaverse-based learning programs through brain activation measurements remains limited.

Therefore, we aimed to neurologically explain brain activity observed during metaverse-based biological classification activities in this study. We selected tidal pool and coastal dune ecosystems, implemented them in the metaverse, and embeded animal and plant classification activities on the metaverse to high school students. Functional Near Infrared Spectroscopy (fNIRS) was used to measure brain activity in a naturalistic setting, and the same inquiry activities were provided in a video lecture format for comparative analysis.

Methods

Participants

This study was approved by the Institutional Review Board (IRB) of the author's affiliated institution (KNUE-202212-SB-0447-01). A total of 24 high school students from grades 10 to 12 in the Chungbuk region, who voluntarily agreed to participate in the study with parental consent, were recruited. All participants were healthy students with no cardiovascular or neurological disorders and had not studied the classification unit of the Life Science II curriculum. Based on the handedness test (Oldfield, 1971), one left-handed student and one student with measurement errors were excluded, resulting in the analysis of brain activity data from 22 students. The number, gender, and age distribution of the final study participants are shown in Table 1.

Table 1. Demographic information of participants

Gender	High school Grade			Number of participants	Age
	1st	2nd	3rd		
Male	10	2	3	15	M = 16.5
Female	4	3	-	7	SD = 0.72

Development of Program

This study utilized the ZEP platform (ZEP Co Ltd; https://zep.us/) to create a metaverse environment representing tidal pool and coastal dune ecosystems. ZEP is a metaverse platform focused on 2D pixel art, enabling communication similar to real life. Its simple structure, user accessibility, ease of operation, and diverse interactive content make it educationally advantageous (Kim et al., 2022). Most importantly, it allows users to easily design and utilize educational content according to their requirements, facilitating teachers' use in actual educational settings (Gwak & Shin, 2023).

Developing a Metaverse for Biological Classification Activities

The metaverse utilized in this study is a modified and supplemented version of what was developed by Kim et al. (2024). For the biological classification activity, a metaverse environment modeled after the tidal pools and coastal dunes of Taean Coastal National Park in Chungnam was created, as shown in Fig. 1. In the tidal pools, animal classification activities were conducted, while plant classification activities took place in the coastal dunes. Metaverse objects representing organisms native to these ecosystems were placed in their respective habitats. Through interaction activities, these objects allowed participants to observe organisms and obtain various information via videos, images, and text, as depicted in Fig. 2. The developed metaverse was refined and revised through preliminary tests involving three current biology teachers and three high school students. Ultimately, metaverse objects representing seven species per ecosystem were selected and arranged as shown in Table 2.

Fig. 1. An ecosystem developed as a metaverse using the ZEP platform (Left : tide pool, Right : coastal dune)

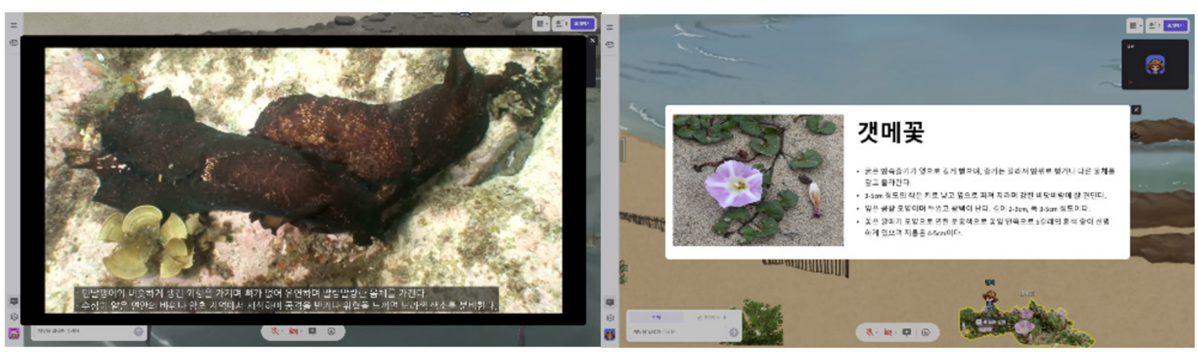

Fig. 2. Information provided by interactions with objects in the metaverse (Left : video and text, Right : image and text)

Table 2. Animals and plants placed in the developed metaverse

Ecosystem	Organism name (Scientific name)
Tide pool (Animal classification)	Striped-body sea anemone(*Haliplanella lucia*), Barnacle(*Pollicipes mitella*), Flat shore crab(*Gaetice depressus*), Sea hare(*Aplysia kurodai*), Korean common dogwhelk(*Thais clavigera*), Longchin goby(*Chasmichthys dolichognathus*), Ribbed gunnel(*Dictyosoma burgeri*)
Coastal dune (Plant classification)	Rugose Rose(*Rosa rugosa*), Beach morning glory(*Calystegia soldanella*), Siberian sea rosemary(*Argusia sibirica*), Sea wheatgrass(*Leymus mollis*), Asian sand sedge(*Carex kobomugi*), Sargassum(*Sargassum fulvellum*), Sargassum thunbergii(*Sargassum thunbergii*)

Metaverse-based Biological Classification Activities

The biological classification activity in the metaverse ecosystem is designed to substitute for actual field activities, which are challenging to conduct in reality. Therefore, the activities carried out in the metaverse system were made to closely resemble those in real field settings. According to Byeon (2022), typical outdoor biological inquiry programs are divided into pre-outdoor activity, outdoor activity, and post-outdoor activity phases. Additionally, Kwon et al. (2000) describe the process of generating classification knowledge as consisting of discovering commonalities and differences among observed objects, devising classification criteria, and applying these criteria. Based on these insights, the biological classification activities in this study were structured as shown in Table 3.

Table 3. Sub-steps of a biological classification activity

Sub-steps	Activity content	Time
Planning biological classification	Organisms a plan for exploring classification criteria by looking at the ecosystem and the list of Organisms, and share it with your group to prepare them for exploring classification criteria.	2min
Exploring classification criteria	Explore the ecosystem to learn about organisms and find appropriate classification criteria. (Personal activity)	7min
Selecting and applying the classification criteria	Share with the group your thoughts on appropriate classification criteria, and present the group's chosen classification criteria and the results obtained by applying them.	5min

In this study, the metaverse-based biological classification activity was conducted in groups of three students. As the first phase of the three-step activities, the planning stage involved preparations before actively exploring classification criteria. In a virtual classroom within the metaverse, students observed images depicting the ecosystem and the locations of various species, and they planned and presented strategies for exploring classification criteria. Through voice communication, group members shared, compared, and refined their individual plans, preparing for the subsequent exploration. In the next phase, the classification criteria exploration stage, students moved to the metaverse-implemented ecosystem to interact with biological objects and gather information on the organisms to identify suitable classification criteria. This stage was conducted individually, where students examined commonalities and differences to find appropriate classification criteria. The final phase, the classification criteria formulation and application stage, involved sharing and comparing the explored criteria with group members through discussions to select the best classification criteria and presenting the classification results.

To compare with the metaverse-based biological classification activity, a video lecture-based classification activity was conducted following the same stages as outlined in Table 3. However, the same content presented in the metaverse was recreated in PowerPoint, and a teacher demonstrated the inquiry activities in a video lecture format. During the planning phase, participants were shown images depicting ecosystems and the positions of various organisms, and they were instructed on how to design a plan for exploring classification criteria. In the subsequent phase of exploring classification criteria, information about the organisms was provided, and the process of identifying potential classification elements was demonstrated. In the final phase of developing and applying classification criteria, participants selected appropriate criteria and categorized the organisms into distinct groups. Students watched the video lecture to understand the teacher's process of conducting the biological classification activities, reflecting traditional lecture-based teaching methods in the classroom. This study aimed to compare metaverse-based activities, in which students generate and apply their own classification criteria, with video lecture-based activities, where students learn through understanding teacher-generated classification criteria.

Data Collection and Analysis

Task Paradigm Design

This study employed a block design method to measure brain activity during metaverse and video lecture-based biological classification activities, with the task presentation paradigm shown in Fig. 3. During the measurement guidance phase, participants were informed of important considerations. In the resting phase, participants closed their eyes and rested for one minute. Following this, the task guidance phase involved explaining the tasks to help participants understand them before performing the tasks after the rest period. Task performance was conducted in one of four cases, depending on the activity form (metaverse or video lecture) and ecosystem (tidal pool or coastal dune), to prevent order and learning effects.

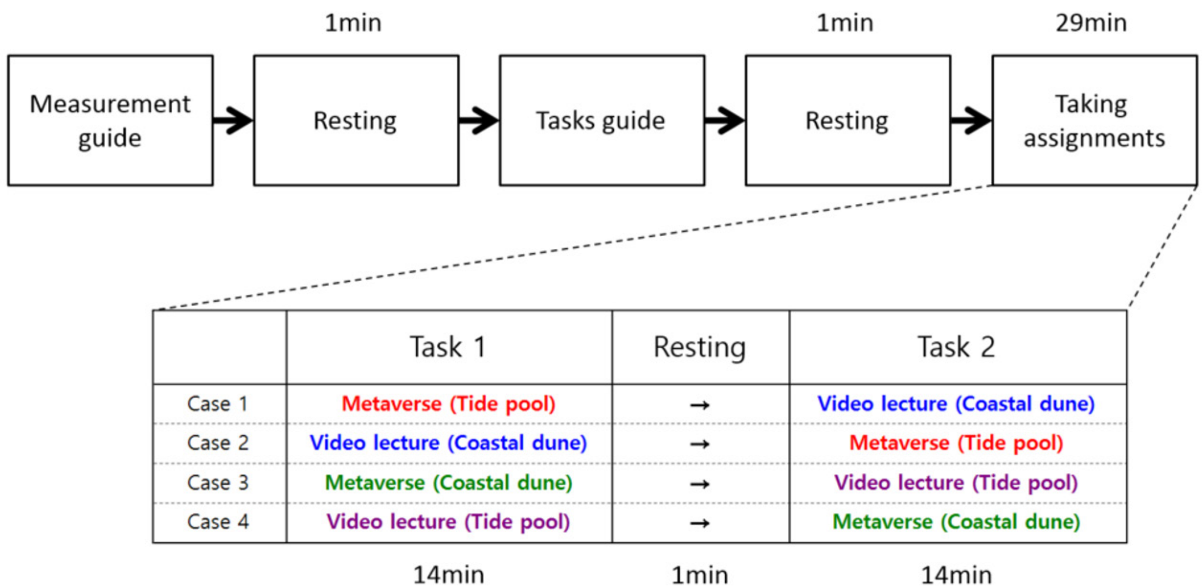

Fig. 3. Task paradigm

Measurement and Data Collection

The brain activity measurement device used in this study is the NIRSIT by OBELAB (model: NS1-H20A; OBELAB, Seoul, Korea), which is worn on the forehead to primarily measure the frontal lobe, where higher-order cognitive processes occur (OBELAB, 2022). As shown in Fig. 4, the measurements were conducted in a quiet environment, with a white wall placed in front of the participant to avoid visual distractions. The monitor displaying the biological classification activity tasks was positioned at the student's eye level. To the student's right, an operator was seated to provide guidance on the measurement procedure and to monitor the participant's responses throughout the process. Behind the student, a computer for collecting brain activity data was set up, with another operator seated to record markers for each activity stage in accordance with the task sequence during data collection with the NIRSIT device. These markers were later used for stage-specific analysis during data processing.

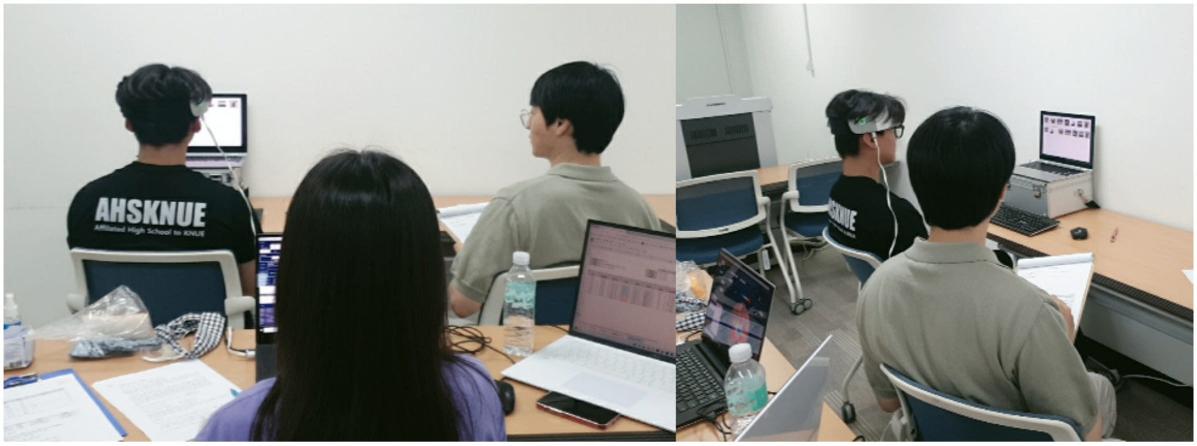

Fig. 4. Measurement environments and measurement scene

Data Analysis

The collected raw data were analyzed using the NIRSIT Analysis Tool (v3.8.4; OBELAB, Seoul, Korea). Initially, in the preprocessing phase, the relevant segments for analysis were selected, and task numbers were assigned. A signal-to-noise ratio (SNR) threshold of 20 dB was applied, excluding channels below this intensity. To remove unnecessary noise caused by physiological factors or movement, a high-pass filter (DCT 0.005Hz) and low-pass filter (DCT 0.01Hz), along with the Temporal Derivative Distribution Repair (TDDR) algorithm, were utilized. Lastly, the Modified Beer-Lambert Law (MBLL) was applied based on the rest state with closed eyes to calculate the oxyhemoglobin concentration in the blood. Following preprocessing, the data were subjected to both individual-level statistical analysis and group-level statistical analysis to determine brain activation levels for each student during the metaverse and video lecture-based biological classification activities. Regression coefficients (β values) were calculated through General Linear Model (GLM) analysis, and all GLM analysis results were visualized by highlighting channels showing significant brain activation at an $\alpha = 0.05$ level through single-sample t-tests. Finally, comparisons were made between the entire process and each sub-stage of the biological classification activities for metaverse vs. resting (Metaverse > Resting) and metaverse vs. video lecture (Metaverse > Video lecture).

Results and Discussions

Brain Activation throughout the Entire Biological Classification Activity

The overall brain activation during the metaverse-based biological classification activity is shown in Fig. 5. When compared with the resting state, significant activation increases were observed in channel 10 of the right VLPFC region and channel 47 of the left OFC region. When compared with the video lecture-based biological classification activity, significant activation increases were observed in channel 20 of the left DLPFC region.

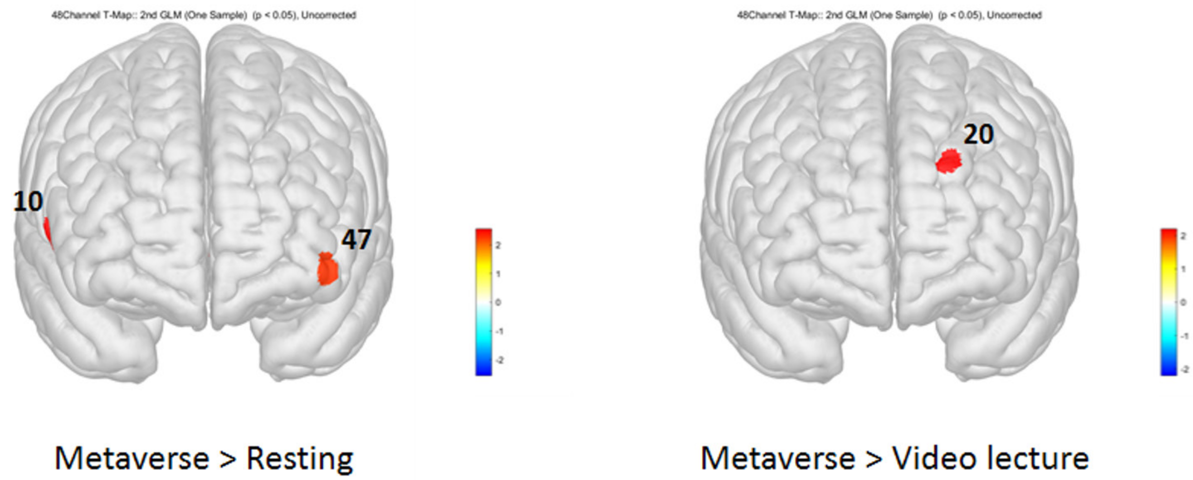

Fig. 5. Brain activation throughout the entire biological classification activity

The right VLPFC is involved in decision-making under uncertain conditions (Levy & Wagner, 2011) and is known to play a role in the visual memory comparison of new information (Wagner et al., 2001). The OFC plays a central role in motivation-reward during task performance (Lee et al., 2012) and is known to integrate relevant information, assign subjective value to cognitive choices, and motivate goal-directed behavior (Ballesta et al., 2020; Stalnaker et al., 2015). The DLPFC is related to maintaining attention, cognitive flexibility (Kaplan et al., 2016; Li et al., 2017), and is involved in maintaining, manipulating, and integrating information in working memory to solve problems (Schmidt et al., 2018; Toepper et al., 2010).

The metaverse-based biological classification activity involves finding similarities and differences to determine appropriate classification criteria. Therefore, it requires a cognitive process of continuously remembering the observed organisms' information and comparing it in working memory. The activation of the VLPFC region can be interpreted as the visual recognition and comparison of new information about organisms in working memory under the uncertain situation where students must find answers on their own. Additionally, the OFC region is activated through the process of motivation and repeated feedback while judging and comparing the value of various classification criteria and their results to find the most appropriate classification criteria.

In contrast, the video lecture-based biological classification activity involves understanding the teacher's classification process. According to Byeon & Kwon (2020), the key brain region for cognitive processes involved in biological classification is the left DLPFC. Maintaining information about organisms in working memory, manipulating and integrating this information to find appropriate classification criteria among several options, requires high levels of attention and cognitive flexibility, which explains the increased activation in the DLPFC region.

Brain Activation in the Sub-Step of the Biological Classification Activity

Planning Biological Classification

When subdividing the metaverse-based biological classification activity into different stages, brain activation during the planning biological classification stage is shown in Fig. 6. Compared to the resting state, significant decreases in activation were observed in channel 40 of the left VLPFC region, while significant increases were observed in channel 47 of the left OFC region. When compared to the video lecture-based biological classification activity, significant decreases in activation were observed in channel 21 of the right FP region, and significant increases were observed in channel 48 of the left OFC region.

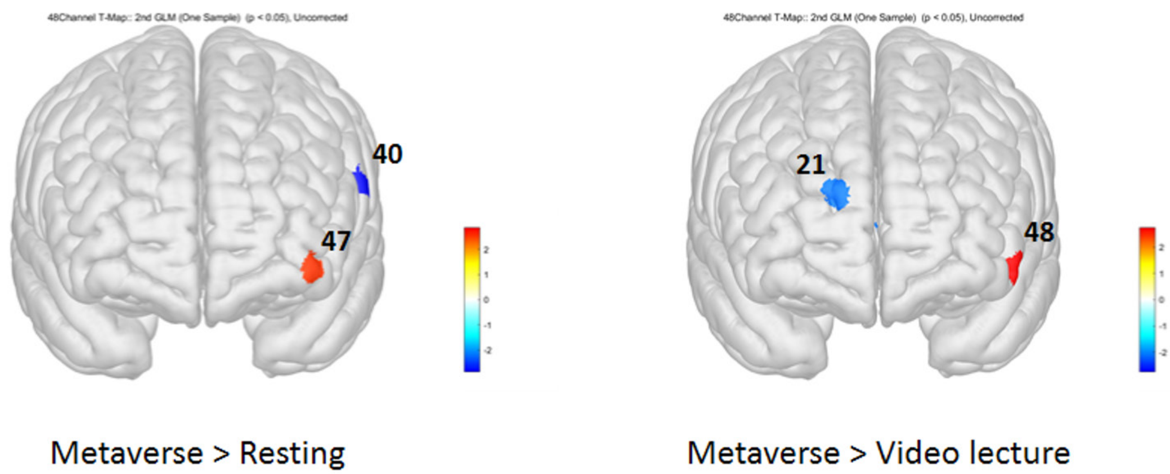

Fig. 6. Brain activation in the first step (planning biological classification) of the biological classification activity

In the planning biological classification stage, students prepare by examining the ecosystem, species list, and their locations, planning their classification criteria before the main inquiry begins. Post-interview responses showed that students were interested in the metaverse activity and expressed anticipation for the unfamiliar task of biological classification. Given the OFC's role in learning motivation, choice, and performance valuation (Ballesta et al., 2020; Lee, Byeon & Kwon, 2012; Stalnaker et al., 2015), this indicates that the planning stage of the classification activity is motivating students. However, there was a decrease in activation in the left VLPFC, a region involved in actively exploring information about stimulus characteristics (Lee et al., 2013) and known to contribute to clarifying information through verbal processing and engaging in decision-making among activated information (Badre & Wagner, 2007; Schendan, 2012). Additionally, it appears that the ventrolateral prefrontal cortex (VLPFC) plays a crucial role in vigilance and resistance to environmental distractions, contributing to attention regulation (Levy & Wagner, 2011). Post-interview results revealed that during the process of sharing plans with their group members, most students struggled with generating exploration plans due to their unfamiliarity with planning. Many reported having no immediate ideas or difficulty determining what kind of plan to formulate. Furthermore, some students indicated uncertainty about what to say. Analysis of actual task performance showed that most students frequently repeated what others had said. According to Modi et al. (2020), reduced VLPFC activation can indicate mental overload, characterized by impaired executive function, loss of attention regulation, and decreased task performance. Therefore, the observed reduction in VLPFC activation may be interpreted as a consequence of difficulties in information exploration and decision-making during the planning process, leading to decreased attention.

Compared to the video lecture, there was higher activation in the OFC during the metaverse-based activity. Post-interviews indicated that students found performing the classification themselves more meaningful and enjoyable than watching the teacher's process. This suggests that metaverse-based activities were more effective in motivating students, leading to higher OFC activation. However, lower activation in the FP was observed, consistent with previous studies using the metaverse (Kim et al., 2024). The FP is involved in planning or strategizing for problem-solving (Koechlin, 2011) and decision-making in open, unstructured scenarios (Burgess et al., 2007; Zajkowski et al., 2017). As noted by Kim et al. (2024), decreased FP activation may be due to the unfamiliar planning activities and the high autonomy and varied objects in the metaverse, which can distract from goal-directed thinking. Thus, this implies that when planning in the metaverse, appropriate teacher control and support are necessary to foster goal-directed thinking.

Exploring Classification Criteria

Brain activation observed during the stage of exploring classification criteria in the metaverse-based biological classification activity is shown in Fig. 7. When compared to the resting state, a significant increase in activation was observed in channel 10 of the right VLPFC region. When compared to the video lecture-based biological classification activity, significant increases in activation were observed in channel 5 of the right DLPFC region and channels 12 and 36 of the bilateral FP regions.

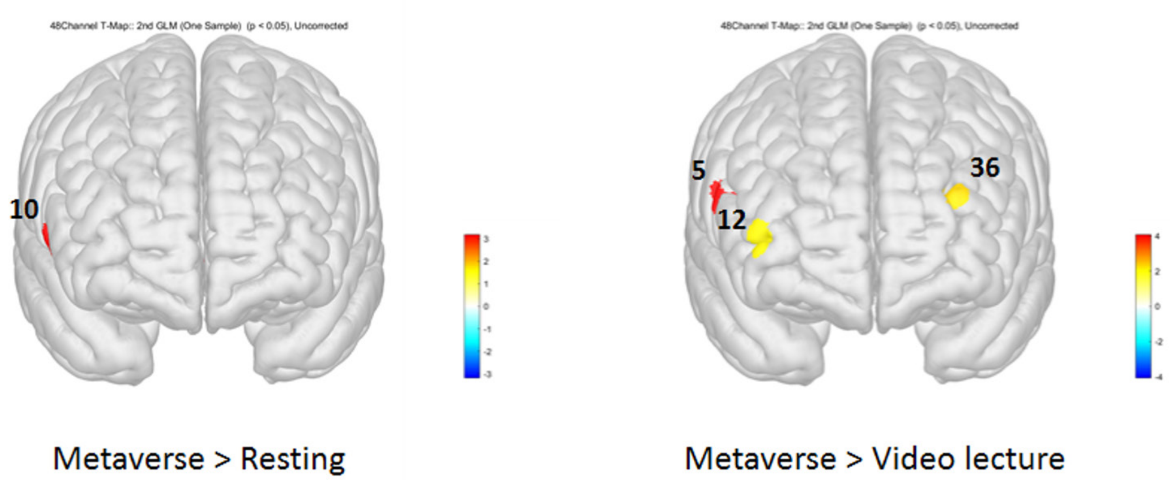

Fig. 7. Brain activation in the second step (exploring classification criteria) of the biological classification activity

The stage of exploring classification criteria corresponds to individual activities and involves interacting with biological objects within the metaverse to identify pertinent classification criteria through the acquisition of biological information. As analyzed, during uncertain situations where individuals must independently seek answers, increased VLPFC activation was observed when new information was visually recognized and compared. Compared to video lectures, the metaverse incorporates a problem-solving process that requires the generation of classification criteria, necessitating high levels of attention and cognitive flexibility. Consequently, higher DLPFC activation is evident. Additionally, increased FP activation was observed, which is associated with goal-directed thinking (Koechlin, 2011; Zajkowski et al., 2017), and is known to engage in higher-order control that adjusts VLPFC and DLPFC functions to maximize task performance (Fletcher et al., 2001). Thus, it appears that FP activation increases to maximize cognitive flexibility and goal-directed thinking during the process of identifying suitable classification criteria. This suggests that biological classification activities in the metaverse stimulate more active goal-directed thinking.

Selecting and Applying the Classification Criteria

The brain activation observed during the final substage, the stage of selecting and applying the classification criteria, is shown in Fig. 8. When subtracted from the resting state, statistically significant activations were observed in channel 6 of the right DLPFC region and channel 47 of the left OFC region. When subtracted from the video lecture-based biological classification activity, significant activations were observed in channel 4 of the right VLPFC region, channels 3, 17, 33, 34, 35 of the bilateral DLPFC regions, and channels 8 and 37 of the bilateral FP regions.

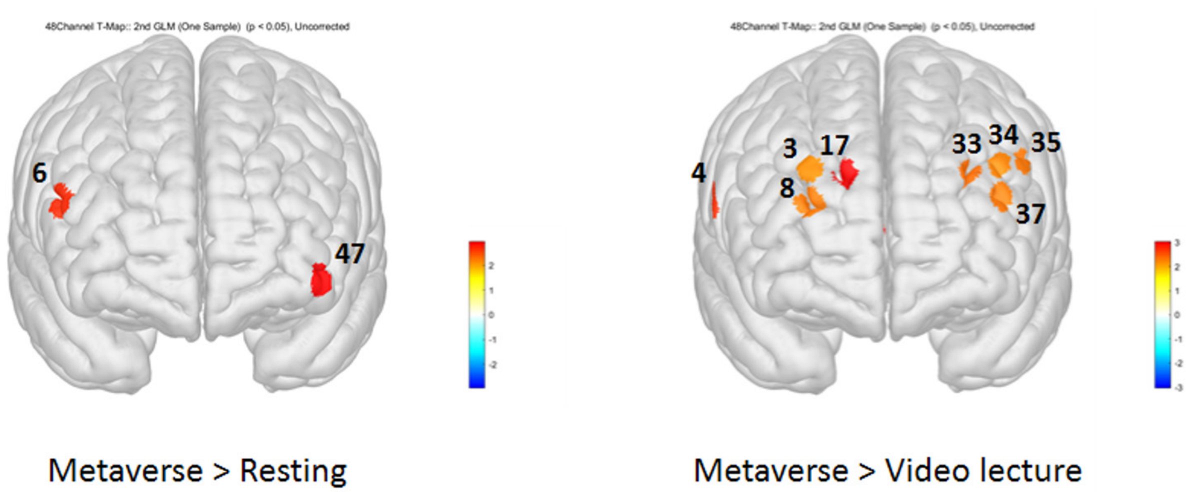

Fig. 8. Brain activation in the third step (selecting and applying the classification criteria) of the biological classification activity

This stage involves sharing and comparing classification criteria developed from the previous exploration stage with team members to select the optimal classification criteria for application. Consequently, while sharing opinions with team members, the cognitive process of continuously monitoring biological information, comparing each other's classification criteria, and identifying the optimal criteria takes place. This requires high levels of attention and cognitive flexibility, leading to increased activation in the DLPFC. Additionally, the OFC region appears to be activated through repeated feedback loops where the value of and comparison between each other's classification criteria are evaluated and synchronized to find appropriate criteria.

Compared to the video lecture, higher activation was observed in the VLPFC, DLPFC, and FP regions. The interaction between the DLPFC and VLPFC is known to play a crucial role in the induction and application of classification rules (Byeon & Kwon, 2020; Goel & Dolan, 2000). Therefore, the interaction between the DLPFC and VLPFC seems to occur during the process of establishing and applying classification criteria with team members. Furthermore, the increased activation in the FP region during this process is presumed to reflect the maximization of cognitive flexibility and goal-directed thinking. Furthermore, the greater number of DLPFC channels activated compared to the individual activity stage of exploring classification criteria indicates that more cognitive effort is required in the process of exchanging information with others in a group setting.

Conclusions and Implications

This study measured and analyzed the brain activation of high school students using fNIRS during the process of metaverse-based biological classification activities, comparing it with video lecture-based biological classification activities, and derived the following conclusions:

Firstly, compared to video lectures, metaverse-based biological classification activities showed a significant increase in activation in the left OFC, right VLPFC, and bilateral DLPFC and FP regions. This is because the process involves solving problems where students must generate their own classification criteria. In this process, students need to visually recognize biological information in uncertain situations and explore the information. They must continuously maintain the recognized information in working memory, compare and integrate similarities and differences to find the classification criteria, requiring high attention and cognitive flexibility. Additionally, the OFC region appears to be more synchronized in the goal-directed thinking process of finding appropriate classification criteria through repeated feedback, where the values of multiple classification criteria and their outcomes are evaluated and compared.

Secondly, when analyzing the metaverse-based biological classification activities by sub-stages, there was a significant decrease in activation in the left VLPFC and right FP during the planning stage. This can be attributed to the unfamiliar investigative planning activities and the high autonomy and learning environment of the metaverse, leading to distraction and decreased goal-directed thinking among most high school students.

Thirdly, when analyzing the biological classification activities by sub-stages, there was a tendency for more activation in bilateral DLPFC channels during group activities compared to individual activities. Group activities involve more opinions than individual ones. Therefore, in the process of maintaining, integrating, and manipulating more information in working memory, higher attention and cognitive flexibility are required.

Based on these conclusions, the educational implications for biology derived from this study are as follows:

Firstly, the neurological evidence provided insight into the brain activation of high school students during metaverse-based biological classification activities. Previous studies that developed various learning programs for biological classification activities presented significant learning effects through interviews or surveys. Furthermore, this study provided neurological evidence that students' cognitive activities for classification indeed occur by measuring brain activation with fNIRS during the biological classification activities.

Secondly, since students are not accustomed to planning for investigations, appropriate support from teachers is necessary. To this end, it is essential to provide sufficient time and materials during the inquiry preparation stage and to offer scaffolding, such as showing examples by teachers.

Thirdly, the potential of the metaverse as a tool for inquiry activities that replace actual outdoor classes was confirmed. Previous studies showed concerns that metaverse use could lead to decreased goal-directed thinking despite its effectiveness in affective domains, such as inducing interest. This study confirmed that implementing a realistic metaverse and presenting concrete problem-solving tasks indeed induced goal-directed thinking among students. Additionally, the study suggests that to maximize meaningful learning, it is essential to actively utilize the advantages of the metaverse, which allows for social interactions similar to real-life, given that cognitive activities were more active during group activities compared to individual ones in biological classification activities.

Conflicts of Interest

The author(s) declared no conflicts of interest.

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