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BRAIN ACTIVITY DURING VIRTUAL LABORATORY ACTIVITIES: AN EDUCATIONAL NEUROSCIENCE STUDY

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ABSTRACT

The COVID-19 pandemic has forced schools and universities to close face-to-face meetings and replace them with online learning activities. Virtual laboratories can be a solution to online learning. So far, no research has revealed the impact of virtual laboratory activities on psychomotor aspects. It was because the psychomotor activity caused by virtual laboratory activities is minimal. This study aims to determine brain activity during laboratory activities. The results of this study were used as a basis for developing virtual laboratory activities that, in theory, have the same effectiveness as real laboratory activities instimulating the central nervous system and engaging the neural networks responsible for psychomotor processes. The type of research used in this study is qualitative research. Qualitative research was chosen as a research method because the naturalistic understanding of qualitative research will help researchers in compiling ground theory. The results of this study indicate that during virtual laboratory activities, the dominant part of the brain that works is the left side, with the most dominant part being the frontal cortex. It shows that thinking activities are more predominant during virtual laboratory activities. This indicates that virtual practicums primarily engage executive cognitive and affective processes while providing minimal stimulation to motor-associated cortical regions (such as the parietal cortex).

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1. INTRODUCTION

The COVID-19 pandemic hit the world in early 2020. The virus originating from Wuhan was officially announced as a global pandemic by WHO on January 30, 2020 (Sohrabi et al., 2020). The COVID-19 pandemic has impacted all aspects of life, including education. The COVID-19 pandemic forced schools and universities to close face-to-face meetings and replace them with online learning activities (Impey, 2020; Panesar et al., 2020).

One of the problems for science teachers in online learning is the implementation of science practicum learning. The study results showed that most science teachers were not ready to conduct practicums online and considered that online practicums could not be implemented (Khusnah, 2020). This happened because teachers considered practicum activities psychomotor activities that could not separated from laboratory equipment and materials.

Virtual laboratory activities can solve online learning (Dewa et al., 2020). Several virtual laboratory activity platforms are available both online and offline. Proteus is a virtual laboratory activity platform for electrical materials that is available offline (Husain & Supriyono, 2015; Suwardi et al., 2021; Yuwono & Suprapto, 2011). Phet Simulation is a virtual laboratory activity platform that can accessed online and offline. Phet simulation is widely used as a virtual laboratory activity platform in science subjects (Astuti & Handayani, 2018; Saregar, 2016; Sari et al., 2015). The study showed that virtual laboratory activities improved learning outcomes (Arnas, 2012; Asrizal et al., 2018; Simbolon, 2015). This shows that in terms of cognitive aspects, virtual laboratory activities can replace real laboratory activities. However, real laboratory activities are learning activities that involve a lot of psychomotor skills. So far, no research has revealed the impact of virtual laboratory activities on psychomotor skills. This is because the psychomotor activity caused by virtual laboratory activities is minimal.

This study aims to determine brain activity patterns during virtual laboratory activities compared to real laboratory experiences. Specifically, it investigates whether virtual laboratory tasks activate only cognitive-related brain regions or also engage the neural command networks responsible for psychomotor activity. The results of this study will be used as a basis for developing virtual laboratory activities that, in theory, have the same effectiveness as real laboratory activities in developing psychomotor aspects.

This study is grounded in a fundamental paradigm of educational neuroscience: all human learning activities, whether cognitive, affective, or psychomotor, are centrally governed by the central nervous system (the brain). Consequently, psychomotor activity is not solely defined by visible physical performance, but fundamentally originates as observable neural activity in specific brain regions, such as the parieta. l cortex which is responsible for motor planning and execution (Huddleston et al., 2021a). (Huddleston et al., 2021)Therefore, observing brain activity provides direct evidence of whether a learning method successfully engages the psychomotor domain at its neural command center. While behavioral measurements are common, there is a critical gap in observing the fundamental neural footprint of psychomotor engagement during virtual laboratory activities via EEG.

This study uses the educational neuroscience perspective to reveal the brain activity that occurs during virtual laboratory activities. Educational neuroscience combines methods and perspectives from brain science, cognitive science, learning science, and educational psychology, which aims to apply neuroscience findings to the education field (Han et al., 2019). Neuroscience can be used to understand what underlies the complex neural and cognitive processes involved in learning mathematical and scientific concepts (Mareschal, 2016). Educational neuroscience allows researchers to understand how the brain works in cognitive work (Feiler & Stabio, 2018).

The novelty of this study lies in its interdisciplinary approach, which combines educational neuroscience with virtual laboratories to investigate cognitive outcomes and brain activation patterns related to psychomotor engagement. This area has been largely unexplored in previous research. Prior studies have demonstrated that immersive virtual environments, such as VR simulations, can support the acquisition of psychomotor skills. For instance, spaced practice using virtual reality (VR) simulators has been associated with better performance and faster psychomotor skill acquisition than massed practice in surgical training (Fahl et al., 2023). Systematic reviews further highlight the importance of instructional design, feedback mechanisms, and virtual environment characteristics in psychomotor training within immersive learning environments

(Mat Sanusi et al., 2025). However, these prior studies focused almost exclusively on behavioral skill outcomes and post-training physical performance. A critical research gap remains regarding neurophysiological investigations, specifically using EEG, to examine whether virtual platforms activate the central nervous system's motor command networks in a manner comparable to hands-on, real-world laboratories.

Additionally, other research has shown that VR applications enhance psychomotor skills in language learning and clinical education; however, these studies primarily focused on behavioral outcomes and did not investigate brain activity (Chen et al., 2020; Krichenbauer et al., 2018; Radianti et al., 2020; Sunarti et al., 2021). This research is important because it addresses a critical gap by exploring whether virtual laboratories activate the brain regions associated with psychomotor processes. This research could provide valuable insights into the potential of virtual labs to replicate the comprehensive benefits of real laboratories in both cognitive and psychomotor domains.

2. METHOD

Research Approach

The type of research used in this study is qualitative research. Qualitative research was chosen as a research method because the naturalistic understanding of qualitative research will help researchers in developing ground theory. The study utilizes an educational neuroscience perspective. Educational neuroscience combines methods and perspectives from brain science, cognitive science, learning science, and educational psychology to apply neuroscience findings to education (Han et al., 2019). Neuroscience helps us understand the complex neural and cognitive processes of learning mathematical and scientific concepts. (Mareschal, 2016). Educational neuroscience allows researchers to understand how the brain works in cognitive work (Feiler & Stabio, 2018).

Research Design

This study began by compiling a worksheet of virtual and real laboratory activities. Furthermore, respondents were asked to do practical activities. During the practical process, brain activity was recorded using EEG. The type of EEG used in this study is EMOTIV EPOC + 14 Channel. EMOTIV EPOC+ 14 Channel is a type of EEG that can be used in neuroscience research outside the health sector (Sugiono et al., 2018, 2019). Respondents' activities during the practicum process and brain activity imaging produced during the process were videotaped. The results of the two videos were then analyzed.

Research Subjects

The participants in this study were $N = 8$ undergraduate science education students (aged 20–22 years; 3 males and 5 females) at Universitas Tidar who were enrolled in the Basic Physics Practicum course. The inclusion criteria required participants to have normal or corrected-to-normal vision, right-handedness, no history of neurological or motor disorders, and no prior exposure to the specific virtual laboratory platform used in this experiment.A purposive snowball sampling strategy was selected to recruit participants. This sampling approach was necessary because EEG experimental setups require non-invasive electrode placement and extended recording periods, necessitating participants who met the strict physiological inclusion criteria and were fully willing to participate. Data collection was stopped when data saturation was reached. In this neurophysiological context, saturation was operationalized as the point where consecutive participant EEG recordings yielded consistent, non-divergent topographical patterns of cortical

activation during the laboratory tasks, indicating that additional sampling would not produce novel activation categories.

Data Sources

The data in the study were in the form of videos of respondents' activities during the practicum activities and videos of brain activity recorded from the results of EEG recordings on a laptop screen. Research subjects generated the data selected using the Snowball technique.

Data Analysis

The research data analysis was adapted from the constant comparison method presented by (Moleong, 2012). Data analysis steps using the constant comparison method include Organizing Data, Data Reduction, Categorization, Synthesis, and Formulating a "Working Hypothesis."

Drawing Conclusions

The conclusion is made by analyzing the tendency of brain activity patterns during the virtual laboratory activity process. The data is then compared with brain activity data during the real laboratory activity process. The research findings will be the difference in activity between virtual and real laboratory activities**.**

3. RESULTS AND DISCUSSION

3.1. Brain Activity During Virtual Laboratory Activities

Based on the results of recording brain electrical activity using EEG EMOTIV EPOC+ show that the left side of the brain is more dominant than the right side during virtual laboratory activities. The results of EEG recordings of eight respondents are presented in Table 1.

Table 1 shows that the left-brain functions more dominantly than the right during virtual laboratory activities. The left brain is associated with thinking, logic, counting, and abstract reasoning (Pinel & Dehaene, 2010; Salillas et al., 2023; Semenza & Benavides-Varela, 2018; Turner et al., 2015). Thus, virtual laboratory activities can be used to train abstract thinking skills. However, practical, and hands-on activities train students to face real situations.

Table 1. Dominant Brain Activity During Virtual Laboratory Activities

Respondent	Left Brain				Right Brain			
	FC*	PC*	TC*	OC*	FC*	PC*	TC*	OC*
R.1	■	■		■	■	■		■
R.2	■	■			■			
R.3	■	■						
R.4	■							
R.5	■							
R.6	■	■			■			
R.7	■							
R.8	■				■			

Information:

*(FC = Frontal Cortex, PC = Parietal Cortex, TC = Temporal Cortex, OC = Occipital Cortex)

■ : High activity

: Moderate activity
: Low activity
: No activity

Keat et al. (2016) stated that someone with a more dominant left brain tends to have better academic abilities. Dülger (2012) stated that the left brain is related to the ability to think mathematically. It can be interpreted that the condition of the left brain that works more actively indicates that the brain tends to work in the cognitive domain. Practical activities based on hands-on activities should activate the brain more in the psychomotor domain.

Table 1 shown that the frontal cortex is the most active part during virtual laboratory activities. This frontal cortex plays a role in cognitive processes (Badre & Nee, 2018a). This reinforces that the dominant frontal cortex during the virtual laboratory activity process shows that virtual laboratory activities tend only to be able to develop the cognitive domain.

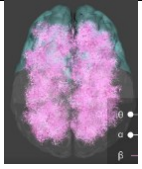
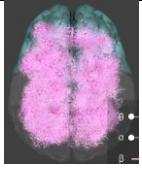
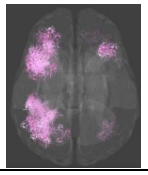
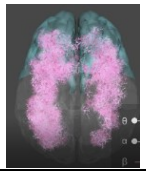
In addition to being responsible for cognitive processes, the frontal cortex is also responsible for affective processes and involves emotions (Kraljević et al., 2021). Thus, virtual laboratory activities can improve learning outcomes in the cognitive and affective domains.

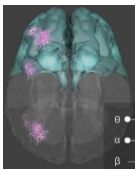
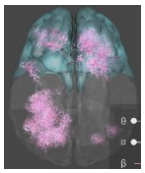
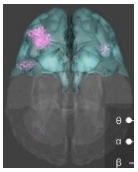
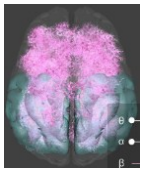
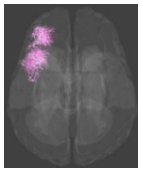
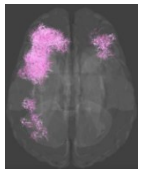
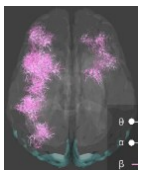
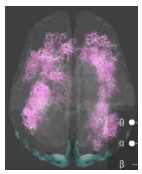
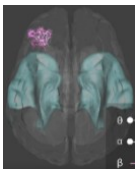
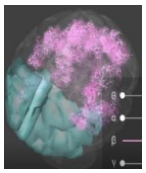
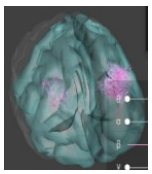
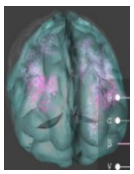
In Table 1, there is an outlier in the data, namely in respondent 1. The results of the brain recording of respondent one during virtual laboratory activities show that all parts of the brain are active. After interviewing respondent 1, information was obtained that respondent 1's academic ability was in the low category. Jin et al. (2019) stated that an effective expert in thinking would use as little brain energy as possible. The activity of almost all parts of the brain of Respondent 1 during the virtual practicum is suspected to be due to Respondent 1's inability to deal with the virtual laboratory activity process. This is confirmed by the results of the EEG recording of respondent one during real laboratory activities that involve higher intensity of brain activity.

3.2. Differences in Brain Activity During the Virtual Practicum Process and Real Laboratory Activities

The results of this study indicate that brain activity during the virtual laboratory activity process is more dominant in involving the brain's left hemisphere, with the dominant part of the brain being the frontal cortex. In contrast, real laboratory activities involve both hemispheres of the brain and almost all parts of the brain. Comparative data between brain activity during virtual and real laboratory activities can be seen in Table 2.

Table 2. Differences in Brain Activity Between Virtual Laboratory Activities and Real Laboratory Activities

Respondent	Brain Activity	
	Virtual Laboratory Activities	Real Laboratory Activities
R. 1		
R. 2		

R. 3		
R. 4		
R. 5		
R. 6		
R. 7		
R. 8		

When interpreted through the central nervous system framework, these findings provide critical insights into the neural mechanisms underlying different learning domains. Because the brain serves as the central command center for all motor execution, the marked absence of parietal cortex activation during virtual laboratory activities reveals a neurophysiological limitation. The parietal cortex plays a pivotal role in sensory integration, visuospatial mapping, and motor planning (Huddleston et al., 2021). In virtual laboratories, student interaction is primarily mediated through subtle computer mouse movements. Consequently, neural resource allocation remains concentrated in the frontal cortex—reflecting high cognitive load and executive control (Badre & Nee, 2018)—while motor command centers remain largely unengaged.

Conversely, real laboratory activities require tactile manipulation, instrument calibration, and spatial coordination, which trigger synchronized activations across both the frontal and parietal networks. This confirms that physical laboratories simultaneously stimulate the neural command centers for both cognitive and psychomotor domains. While EEG patterns indicate central neural resource allocation rather than direct physical performance quality, these

neurophysiological findings demonstrate that current virtual laboratories do not fully engage the motor-associated neural networks required for comprehensive psychomotor training.

Brown & Lee (2025) stated that the left brain is related to structured and controlled experimental activities, while the right brain is related to random experimental activities with little restraint. The dominant left brain during virtual laboratory activities shows that virtual laboratory activities have not been able to bring students into open inquiry practicums. Practicums in higher education should be open inquiry because they can simulate and reflect research and experiments usually carried out by scientists (Zion & Mendelovici, 2012).

Table 2 shows that the parietal cortex is also active during real laboratory activities in addition to the frontal cortex. Huddleston et al. (2021b) stated that the parietal cortex is responsible for motor activity. The parietal cortex during virtual laboratory activities in some respondents was also active with low intensity, but parietal cortex activity was higher during real laboratory activities. Low-intensity parietal cortex activity during virtual laboratory activities is likely due to respondents moving the mouse. Thus, real laboratory activities can be used to develop learning outcomes in the cognitive, affective, and psychomotor domains.

4. CONCLUSION

This study concludes that during the virtual laboratory activity process, the dominant part of the brain is the left hemisphere, with the frontal cortex being the most dominant part. It shows that thinking activities are more predominant during virtual laboratory activities. In addition, virtual laboratory activities are only suitable for developing cognitive and affective learning outcomes.

Brain activity during virtual laboratory activities is more dominant in the left brain. Both activities in the left and right brains are active during real laboratory activities. During real laboratory activities, the parietal cortex and the frontal cortex are also observed. It shows that real laboratory activities can be used to develop cognitive, affective, and psychomotor learning outcomes.

Virtual laboratory activities can only foster cognitive and affective learning outcomes. For this reason, virtual laboratory activities should be designed to train hands-on activities so that they can be used to create the psychomotor domain. Virtual laboratory activities that use augmented reality and virtual reality are considered capable of training hands-on activities.

Virtual laboratory activities tend to show high cognitive activity. Thus, performance during virtual laboratory activities can be used to access cognitive skills related to high-order thinking.

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