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Contents

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Original Article

Blood Oxygen Dynamics in the Brain during Motor Imagery using Virtual Reality

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Abstract: [Purpose] Virtual reality (VR) are few reports of brain activity, such as functional near-infrared spectroscopy (fNIRS) using VR. We used a portable VR to measure brain hemodynamics with fNIRS as a basic study when viewing motion images. [Subjects and Methods] Subjects were randomly assigned, 21 to the 2D group and 21 to the VR group. Both groups performed video motion imagery for 30 seconds. The oxygenated hemoglobin concentration of the surface cerebral blood flow was measured with fNIRS at rest, with motor imagery, and walking and was compared. The questionnaire score were secondary variables. [Results] In video watching, the prefrontal cortex of the VR group had lower activity than the 2D group. In tandem gait, the motor cortex of the VR group had lower activity than the 2D group. In the questionnaire, the VR group score was significantly higher than the 2D group in "Immersive?" And "The video and find it easy?" [Conclusion] VR has a clearer and easier to understand motor imagery than 2D. As a result, the VR group could image the task easily and smoothly. The survey suggested that the immersive nature of VR was a feature of VR. VR is a possible effective tool for motor imaging.

Keywords: Virtual reality, Functional near-infrared spectroscopy, Motion imagery

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I. INTRODUCTION

fNIRS is widely used to measure brain activity during exercise. However, it is difficult to perform exercise such as walking during Positron emission tomography (PET) and magnetic resonance imaging (MRI) measurements [1].

fNIRS can detect the concentration of oxygenated hemoglobin in the blood of the brain cortex by irradiating near-infrared light from the scalp.

Near-infrared light reaches only about 3 cm into the scalp, so it can only measure the surface of the cerebral cortex. Therefore, changes in blood flow in the cerebellum and brain stem cannot be measured. Probe spacing is related to the depth of the near-infrared light. Spatial resolution is inferior to fMRI and PET (about 2–3 cm).

Virtual reality (VR) has been used for treatment, therapy, and surgery. It is also used for rehabilitation. VR allows the user to experience a world created by a computer as if it were real. The characteristic of VR is that it is a real-time simulation involving virtual element interaction. It is the ability to immerse oneself in a virtual environment. It is divided into a large installation and a portable type that uses a head-mounted display and has various uses.

VR is defined as a combination of three elements [2]. The first is "real-time interaction," which refers to the interaction between time and real-time in a three-dimensional space. The second is "three-dimensional

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spatiality," which indicates the extent of the three-dimensional visual and auditory spaces. Third, it is a "self-projection," which refers to the state in which you are in the computer space.

There are three main features of rehabilitation using VR. First, two-dimensional images are more likely to induce a sense of visually guided self-motion. Hence it is easy to grasp the distance and feel the speed, so it is easy to imagine the movement [3]. Second 93.5% of participants reported a sense of accomplishment and satisfaction [4]. Therefore, psychological factors such as fun and motivation are involved. The third is that it is effective for balance exercises. There are reports on image motion in VR. The VR system can promote better outcomes to improve posture control after exercise in the standing position balance of healthy adults [5]. There is also a systematic review of VR training [6-7]. However, there are no randomized control trials of motor imagery using VR, only single case reports or intervention studies.There are few reports of brain activity with functional near-infrared spectroscopy (fNIRS). Evidence regarding brain activity using portable VR is needed. Therefore, we used a portable VR to measure cerebral hemodynamics with fNIRS as a basic study when performing motion imaging. We also compared cerebral blood flow dynamics when motor imagery is obtained in VR and 2D video.

In this study, we checked the effects of different imagery in VR and 2D videos on surface cerebral hemodynamics and gait speed.

It has been reported that brain activity works in the early stages of learning and decreases as learning takes hold [8]. In addition, activity in Primary Visual Cortex during kinesthetic motor imagery with action observation minus action observation alone was inversely associated with vividness of kinesthetic motor imagery within and across participants [9]. Others have reported that during motor imagery of whole-body movements, the Premotor area and Supplementary motor area were more activated by difficult tasks such as imagery of standing with an external perturbation or walking on an irregular surface than by imagery of easy tasks such as static standing or walking on a smooth surface [10].

Therefore, we hypothesized that brain activity would be less active if the motor images were easier using VR.

II. PARTICIPANTS AND METHODS

1. PARTICIPANTS

The study design compared the means of two prospective independent groups. The 42 participants, 21 healthy adult males and 21 females (mean age 23.2 ± 3.4 years) randomly divided into a VR group (mean age 22.6 ± 2.5 years) and a 2D group (mean age 23.6 ± 3.9 years). The purpose of the study was explained, and all participants provided informed consent. The subjects are self-reported right dominant hand and foot with no dominant hand compulsion. The subject must have never used VR before. They had no history of orthopedic or cerebrovascular disease.

G-power [11] was used to determine the sample size. The total sample size was set at 42 subjects when the effect size was moderate (f = 0.7). The significance was set at 0.05, and the power was 0.6 in the preliminary analysis.

2. METHODS

We used a LIGHTNIRS near-infrared spectroscope (Shimadzu Corporation, Kyoto, Japan).

The setup was based on a previous study [12] (Figure 1). Transient changes in blood pressure may be reflected in NIRS measurements. Therefore, blood pressure and pulse were measured before and after the experiment. NIRS can also be affected by cutaneous blood flow; therefore, room temperature during measurement was set at 25°C with air conditioning. Participants were also instructed not to move because the head movement can cause noise.

It is difficult to position the measurement areas anatomically. The international 10–20 method was used as in previous studies (Figure 2). The target areas of fNIRS were the prefrontal cortex, premotor cortex, supplementary motor cortex, and primary motor cortex measured at 1 to 20 channels. The VR device used was the VR180 (Lenovo Group Limited, Beijing, China), a head-mounted display used to watch the VR video (Figure 3). This device can transfer the filmed video to the head-mounted display for watching VR video. The image quality is 13 million pixels, and the viewing angle is 110°.

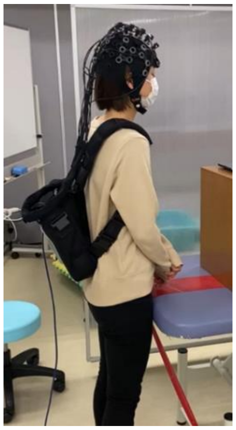

Figure 1. LIGHTNIRS device.

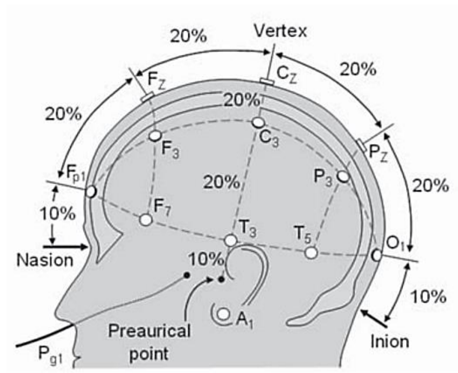

Figure 2. The 10–20 method.

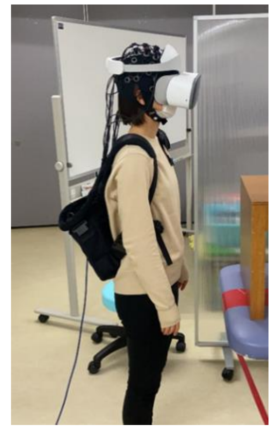

Figure 3. VR180

The group that viewed the exercise with the VR device was defined as the VR group. The group that viewed the exercise on a PC screen was defined as the 2D group. A first-person image video was used for the exercise video. The characteristic of a first-person image video is that the viewer can experience the same changes in vision and sound as the filmmaker. This characteristic gives the viewer a sense of realism as if the viewer is exercising. The study protocol is shown in Figure 4.

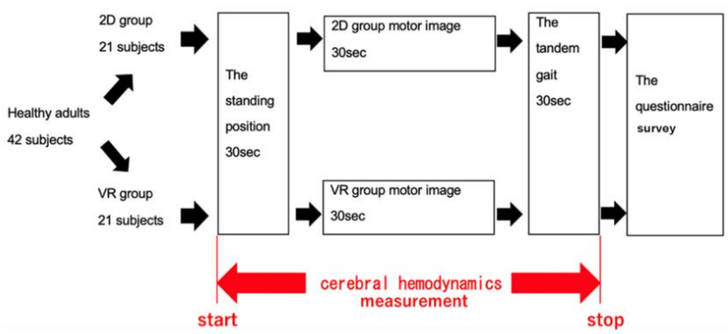

Figure 4. The study protocol algorithm.

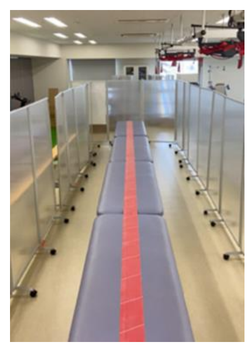

Figure 5. Tandem walking environment.

Cerebral blood flow was measured for 30 seconds in the standing position with the eyes closed at rest in the VR and the 2D group. Subsequently, the motor imagery while watching the first-person VR or 2D video in the standing position was measured for 30 seconds. After that, measurement was performed for 30 seconds while standing with the eyes closed. Brain activity during motor imagery and actual exercise was compared. The video watching environment was in the standing position. The length between the PC and the subject was 50 cm [13)]. The oral instructions for the task were "Please imagine yourself as if you were tandem walking." The video time was 30 seconds, and the walking speed of the video was 23.7 cm/sec.

After the exercise image, the subject rested for 1 minute. The motor task was to perform tandem walking on an elevated bed. The walking speed was set at a comfortable speed. The bed had a red line drawn in the center to make it 32 cm wide and 75 cm high (Figure 5).

The measurement was made for 30 seconds while standing with the eyes closed at rest on the elevated bed. Tandem walking was subsequently measured on the elevated bed for 30 seconds. After that, the standing position with eyes closed on the elevating bed was measured for 30 seconds.

Evaluation items

There were three evaluation methods. The first was the amount of oxygenated hemoglobin (Oxy-Hb) measured by NIRS. fNIRS measured changes during video watching and the amount of change during walking from a resting position in the 2D and VR groups. The 2D group and the VR group were compared. The change in Oxy-Hb at rest standing and during the task was compared.

The second measure was the tandem walking speed. The walking speed was measured in both groups. Walking speed between the 2D group and the VR group was compared.

The third was a questionnaire survey. After measurements, we applied a questionnaire and compared the two groups. The questionnaire had a 10-point scale, except for item (5), "I do not think so at all," which was set to 0, and "I agree very much," which was set to 10. The answers were given in 10 steps, and both groups were compared.

We compared the efficiency of the subjective motor imagery and the reproducibility of fear of the image stimulus of 2D and VR.

The following questions were used.

(1) Did you feel video sickness?
(2) Were you afraid during the imagery?
(3) Were you able to perform the exercise as you imagined?
(4) Did you feel an immersive experience?
(5) Do you have any experience with VR? If yes, how many times?
(6) Did you see the video and find it easy to do?

Statistical analysis

Changes in Oxy-Hb between the 2D group and the VR groups were analyzed to compare the two groups. This measure was made from the resting position during the video watching and walking task. The walking speed of the 2D group and the VR group was compared, and the questionnaire survey was analyzed to compare the response of the 2D and the VR group. After determining normality, the Mann–Whitney U test was performed for non-normal distributions. Analyzes were performed with IBM SPSS version 22. The significance level was set at 5%.

III. RESULTS

The results of the NIRS are shown in Tables I and II. During video watching, the activity of the prefrontal cortex of the VR group was lower than the 2D group with no significant difference in other regions. In tandem gait, the activity of the motor cortex of the VR group was lower than the 2D group with no significant difference in other regions.

Walking speed was 20.75 ± 4.9 cm/sec for the 2D group and 22.01 ± 5.5 cm/sec for the VR group. There was no significant difference between the two groups.

The VR group had a significantly higher score in the questionnaire in (4) “Did you feel immersive?” And (6) “Did you see the video and find it easy to do?” (Table III).

Table I. Comparison between two groups of motor imagery and change in resting standing position.

Cortical area	2D(Average)	VR(Average)
Prefrontal cortex* (IQR)	0.0063 (0.0007 - 0.0090)*	0.0047 (-0.0142 - 0.0065)
Left premotor cortex (IQR)	−0.0006 (-0.0028 - 0.0044)	−0.0027 (-0.0083 - 0.0002)
Supplementary motor cortex (IQR)	0.0013 (-0.0023 - 0.0060)	−0.0013 (-0.0058 - 0.0002)
Right premotor cortex (IQR)	0.0023 (-0.0018 - 0.0038)	0.0012 (-0.0086 - 0.0021)
Primary motor cortex (IQR)	0.0047 (-0.0015 - 0.0066)	−0.0027 (-0.0083 - 0.0002)

*$p < 0.05$

Table II. Comparison between of walking and resting standing position groups.

Cortical area	2D(Average)	VR(Average)
Prefrontal cortex (IQR)	0.0224 (0.0073 - 0.0376)	0.0446 (0.0106 - 0.0629)
Left premotor cortex (IQR)	0.0140 (0.0059 - 0.0354)	0.0258 (0.0027 - 0.0371)
Supplementary motor cortex (IQR)	0.0147 (-0.0048 - 0.0298)	0.0108 (-0.0079 - 0.0272)
Right premotor cortex (IQR)	0.0196 (0.0076 - 0.0320)	0.0132 (-0.0064 - 0.0271)
Primary motor cortex* (IQR)	0.0392 (0.0089 - 0.0392) *	0.0258 (0.0023 - 0.0374)

*p < 0.05

Table III. Questionnaire survey data. (Average)

Video	(1) Did you feel video sickness?	(2) Were you afraid during the imagery?	(3) Were you able to perform the exercise as you imagined?	(4) Did you feel an immersive experience?	(5) Do you have any experience with VR? If yes, how many times?	(6) Did you see the video and find it easy to do?
2D(IQR)	1 (1 - 1)	1 (1 - 3)	5 (3 - 8)	3 (3 - 5) *	0 (0 - 1)	5 (3 - 6) *
VR(IQR)	1 (1 - 1)	2 (1 - 3)	6 (5 - 8)	7 (5 - 7)	1 (0 - 2)	6 (5 - 8)

*p < 0.05

IV. DISCUSSION

Walking speed was not significantly different between the 2D and VR groups, but the VR group had a walking speed that was closer to the video walking speed.

The questionnaires were designed to answer the questions "Did you feel immersed?" in (4) and "Did you feel comfortable watching the video?" and (6), "Did you find it easier to do the exercise when you saw the images? (6), but no significant differences were found for the other questions.

Functional near-infrared spectroscopy group comparison showed that the difference between the 2D and VR groups was significantly lower in the VR group in the prefrontal cortex during imagery. During walking, the primary motor cortex showed significantly lower values in the VR group.

This was discussed as follows.

The activity of the prefrontal cortex of the VR group was significantly lower than the 2D group. The role of the prefrontal cortex is working memory [14)] and control of behavior [15-16)]. reported that motor imagery showed activity in the prefrontal cortex. In this study, the 2D image was created by watching a PC.

VR was displayed with a head-mounted display. Therefore, VR has no visual information other than the image. In other words, VR provides a more immersive experience.

Goto et al. reported that three-dimensional images are more likely to induce visually induced self-motion sensation than two-dimensional images (3). In addition, it is reported that visually-induced self-motional sensation improves motor imagery ability [17)]. From the previous study, it is considered that VR facilitates motor imagery in this study as well. It is thought that it was easy to imagine in the VR group. As a result, the VR group showed significantly lower brain activity than the 2D group. The motor cortex activity in the VR group tandem gait was significantly lower than in the 2D group. It has been reported that motor imagery is related to the planning and programming of exercise [18)].

Motor imagery is effective in improving actual performance [19)]. reported that groups with greater image clarity and control perform better. During learning, there is an activation of the premotor cortex and the supplementary motor cortex, whereas with practice, these activations decrease [20)].

Motor imagery in VR is clearer and easier to understand than in 2D. Therefore, the motor cortex activity in the VR tandem gait was significantly lower than the 2D group. As a result, the VR group could image the task easily and smoothly.

There was no significant difference in walking speed between the two groups. There was no effect on speed between VR and 2D for the same video.

For walking speed, a simple numerical comparison showed a difference of approximately 1.26 seconds. However, no statistical significant difference was observed. There was no significant difference between the two groups in walking speed. This may be because the questionnaire survey showed no significant difference between the two groups in the question "Did you perform as you imagined?

However, the VR group's walking speed was 1.7 m/sec closer to the image speed, suggesting that the use of VR may allow the participants to naturally control their walking speed without verbal instructions.

In the questionnaire, questions (4) "Did you feel immersive?" and (6) "Did you see the video and find it easy to do?" had a significantly greater affirmative response in the VR group. Question (4) shows that VR creates a feeling of being in the image. In question (6) the "ease of doing" can be easily imaged by expanding the visual space in the three dimensions.

As mentioned before, VR has three main features for rehabilitation. First, it is easy to grasp the distance and feel the speed, so it is easy to imagine the movement. The second is that psychological factors such as fun and motivation are involved. The third is that it is effective for balance exercises. As a result, immersion, and ease of doing influence NIRS results.

The limitations of this study were that the brain area of each subject is not necessarily the same due to the different shapes of their head. Second, in the NIRS measurement, the signal amplitude varies depending on the position of the irradiating and receiving fiber pairs. Therefore, a comparison of the amplitude of the NIRS signal between sites or individuals is not a comparison of the size of the blood flow response (6). Third, motor imagery is inaccurate because it lacks objectivity and reproducibility.

Conclusion

It was easy for the VR group to use motor imagery. As a result of the questionnaire survey, subjective preparation for exercise was smooth. However, there was no statistically significant difference in walking speed performance. As a study limitation, there was not enough data to produce a statistically significant difference in walking speed.

In this study of using the G-power, the statistical power was set at 0.6. However, it was needed 68 (34-34) subjects at the statistical power of 0.8.

Using VR can feel immersive, and it is easy to transition into motion. VR is an effective tool for motor imagery.

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FUNDING AND CONFLICT OF INTEREST

The authors declare that no competing interests exist.

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