UNIVERSITY
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Summary
of Doctoral Thesis

Mehrdad Naderi

APPLICATION OF THE ELECTROENCEPHALOGRAPHY METHOD TO STUDY THE VOLUMETRIC THREE-DIMENSIONAL VISUAL PERCEPTION

Riga 2024

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FACULTY OF PHYSICS, MATHEMATICS AND OPTOMETRY

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APPLICATION OF THE ELECTROENCEPHALOGRAPHY METHOD TO STUDY THE VOLUMETRIC THREE-DIMENSIONAL VISUAL PERCEPTION

SUMMARY OF THE DOCTORAL THESIS

Submitted for the Doctoral degree in natural science
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The doctoral thesis work was carried out at the Department of Optometry and Vision Science, Faculty of Physics, Mathematics and Optometry, University of Latvia from 2020 to 2024.

The thesis contains an introduction, five chapters, and a reference list. The thesis is written in English language on 79 pages, which consist of 40 figures, 1 table, and 131 references.

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ABSTRACT

Doctoral thesis was written in English language on 79 pages, which consist of 40 figures, 1 table, and 131 references. The thesis aimed to study the application of the Electroencephalography (EEG) method to evaluate the volumetric three-dimensional (3D) visual perception. The study compared a novel "volumetric multiplanar display" to traditional flat screens as an anaglyph 3D system. EEG effectively measured brain activity during 3D perception tasks. The brain responded differently to different depth presentation methods. In volumetric display, P3 component of Event-Related Potentials (ERP) showed significant differences compared to anaglyph display. Power Spectral Density (PSD) analysis showed a higher brain activity in anaglyph compared to volumetric display and exhibited hemispheric asymmetry. In addition, P3 component was higher in 2D volumetric perception over 3D. Finally, the depth perception on the volumetric display was easier in dim lighting conditions.

In conclusion, EEG is a valuable tool for studying brain activity during 3D visual tasks on different imaging technologies. This study contributes to the understanding of how the human visual system perceives depth and how it can be assessed objectively. In the last studies assessing the impact of different imaging technologies on human perception.

Keywords: electroencephalography, volumetric multiplanar display, visual search, depth perception, event-related potential, power spectral density

CONTENTS

1. INTRODUCTION

1.1 Motivation

The brain is a complex network of neurons that work together to process information. Brain-Computer Interfaces (BCI) can be used to study these connections and understand mental states. BCIs are becoming increasingly popular as scientists try to learn more about how the brain works. Three-dimensional (3D) displays offer a new way to experience information by creating a sense of depth and volume which can be used to improve the viewing experience and make it easier to visualize information [1].

The crucial question is whether the depth effect produced by the new display is with slightest visual symptoms regarding the accommodation-vergence conflict [2]. Therefore, assessing the ergonomics of three-dimensional visualization systems has become essential in terms of depth perception [3][4].

The evaluation of 3D display interaction with our visual system can be done through subjective or objective methods, each with its own advantages and drawbacks. Among objective methods, Electroencephalography (EEG) stands out as a powerful neuroimaging technique. EEG is favoured for its excellent temporal resolution, non-invasiveness, and relatively low setup costs, making it the most commonly used technique for capturing brain signals in studies related to 3D display interaction [5].

1.2 Structure of the thesis

1.2.1 Aim

The aim of the thesis was to develop an Electroencephalography (EEG) application that could monitor brain activity while individuals perceive a three-dimensional image displayed on a volumetric multiplanar display.

1.2.2 Objectives

1. to assess the brain activity by viewing 3D images on a volumetric multiplanar display;
2. to determine and compare the value of event-related potential (ERP) components as well as power spectral density (PSD) for real and simulated 3D images produced by different imaging technologies;
3. to assess the effect of external conditions such as illumination as well as task repetition on the cortical activity;
4. to evaluate the application of the EEG for objective assessment of depth perception.

1.2.3 Hypothesis

The thesis hypothesized that the amplitude and latency of ERPs could be influenced by various visualization systems, such as volumetric multiplanar displays and stereoscopic anaglyph displays. Additionally, it was suggested that brain activity, might also be affected in a way that there is higher brain activity in stereoscopic anaglyph over volumetric display. Furthermore, it was hypothesized that environmental illuminance has no significant effect on the visual task performance on a volumetric display.

1.3 Novelty of work

The thesis proposes a novel method for evaluating depth perception, addressing the lack of objective methods in this area. Current approaches primarily rely on subjective assessments, which are prone to bias and guesswork. Additionally, subjective methods often focus solely on binocular disparity depth cues, neglecting other depth cues used by the human visual system. By recording and analysing brain data while subjects perceive 3D images containing multiple depth cues, the proposed method aims to objectively evaluate depth perception, bringing it closer to real-world experiences. While there may be drawbacks to the new method, it holds promise for assessing depth perception and uncovering the underlying processes involved in different types of depth perception, such as global and local cues.

2. LITERATURE REVIEW

2.1 Introduction

Understanding the mechanisms underlying the functioning of the human brain is a great challenge in developing algorithms and models of visual perception. Developing non-invasive methods for recording brain activities provided many opportunities to discover different aspects of human brain in theme of perception, cognition, and memory. Moreover, objective evaluation of new developed devices and instruments, which interact with the human vision, is accessible easily by measuring and analysing the brain activity. To understand the basic principle of the mentioned interaction, we need to know the function of human visual system and the structure the developed device. The current thesis focused on the developing an EEG algorithm of depth perception in a 3D volumetric multiplanar display.

2.2 EEG studies on the visual system

Several studies in the field of visual search have been designed to incorporate EEG signal recording and analysis. In this context, some of the most pertinent concepts related to the current thesis were reviewed briefly.

Alex Dan and Miriam Reiner reported that cognitive load of processing events in 3D virtual worlds is lower than processing events in 2D displays. They studied Cognitive Load Index (CLI) as the ratio of the average power of frontal theta band and parietal alpha band [6].

Fazlyyyakhmatov et al. investigated EEG activity while individuals engaged in binocular depth perception of 2D images. They found that when perceiving stereo images with incorrect depth perception, there was a reduction in alpha-band activity in the left parietal region and in the frontal areas of both sides of the brain. However, the activity in the beta-1, beta-2, and delta frequency bands showed no significant changes [7].

In an interesting study, effects of object colour stimuli on human brain activities in perception and attention was investigated by Yoto., et al. They reported that alpha and theta band indicated higher power for red colour presentation than blue stimuli. They conclude that red light activated the central nervous system more strongly than did blue or green light [8]. In addition, another study reported that disparity range for the yellow hue is greater than the red hue, moreover, red is greater than the blue hue and the disparity range for green hue is smallest [9].

2.3 Volumetric Multiplanar Display

Multiplanar 3D displays operate by constructing 3D images, leveraging the persistence of vision to integrate multiple 2D pattern-carrying surfaces into a 3D volume [10]. This approach allows different layers to depict varying depths of the image, utilizing both static and motion parallax to form a 3D image within this technology. Volumetric multiplanar displays offer several advantages, including the ability for multiple viewers to observe them from various angles without requiring stereo goggles, leading to a significant reduction in conflicts.

The Multiplanar Optical Element (MOE) comprises twenty air-spaced depth planes with light diffuser layers synchronized with a high-speed projector. Functioning as an electronically variable solid-state projection volume, the MOE facilitates the reconstruction of a volumetric scene by obtaining 2D slices of the 3D scene [11], as illustrated in Figure 1.

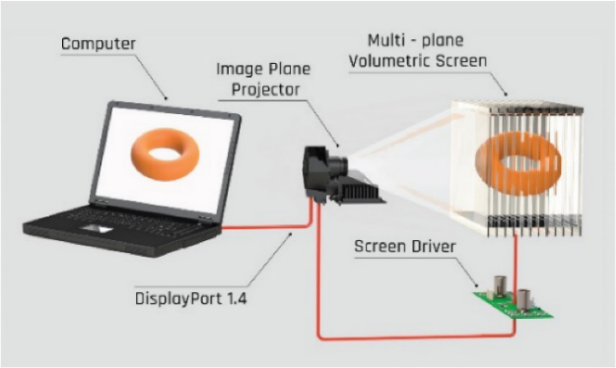

Figure 1. Structure of a volumetric multiplanar display [11].

3. METHODS

In this thesis, several studies were conducted to analyse the application of EEG for depth perception of a 3D image presented on a volumetric multiplanar display.

3.1 Participants

Participants were chosen of any ethnicity. Eighty-one individuals comprising 27 males and 54 females, with an average age of 25 ± 5 years. They voluntarily joined the research, and before commencing the experiment, an informed consent paper signed. Optometric visual tests were conducted to ensure their normal binocular vision function.

3.2 Displays

The visual stimuli were presented on two different types of displays. The first display was a solid-state volumetric multiplanar display (LightSpace Technologies, model: X1907, 19” diagonal and refresh rate of 60 Hz) (*see Figure 2*).

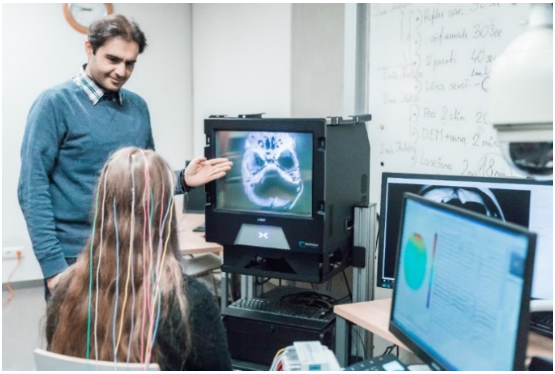

Figure 2. The volumetric multiplanar display employed for the 3D image presentation.

The second type was a flat-panel display (Dell P2417H, 24” diagonal) was used for an anaglyph stereoscopic visualization. The refresh rate was 60 Hz.

3.3 Study design and Task

The general structure of the procedure and task was the same in all experiments with a little difference. The study of “effecting the lighting condition on volumetric 3D image depth perception” was conducted in two different lighting conditions: scotopic, illuminance of 1.2 lux and photopic, illuminance of 1146 lux.

Each experiment included a total of 160 trials. The 3D image demonstration occurred in 50% of the trials un 2D image in 50% of all trials in a randomized order. Each trial started with a fixation cross that was presented in the middle of the screen for 1 sec. Next, four rings (outer diameter – 0.5°, line width – 0.1°) were displayed at 1.0° field eccentricity from the display centre. In the 3D trials, one ring appeared closer to the viewer, shown in Figures 3 (a) and (b). Participants had to report its relative location by choosing one of four responses (up, right, down, and left). Participants sat facing the display at a viewing distance of 90 cm (*see Figure 3(b)*).

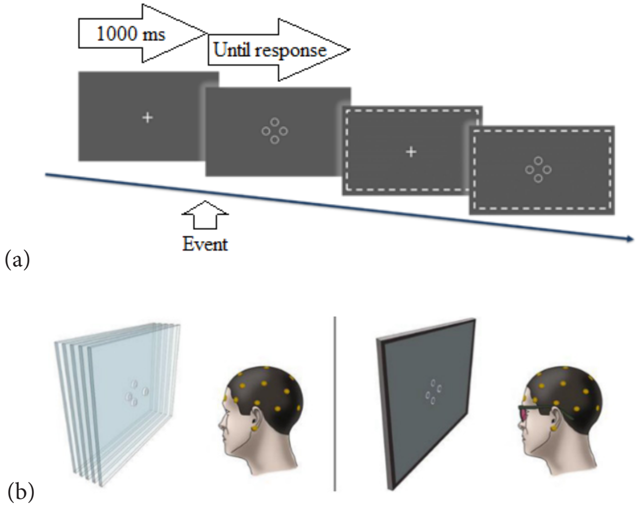

Figure 3. Figure (a) – the experiment designs. Figure (b) – schematic illustration of the setup and stimulus on the volumetric multi-plane display and flat panel display.

In case of flat panel display, crossed and uncrossed disparity experiment, the visual target had the same dimensions as the volumetric visual target. The red-cyan (red filter over the right eye) filters were worn by participants.

Figure 4 shows the visual target in form of anaglyph for crossed and uncrossed disparity.

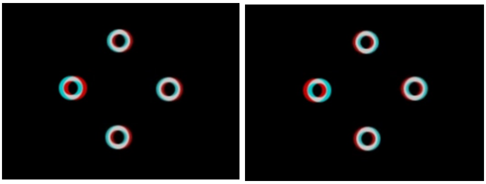

Figure 4. The visual target for the crossed (right) and uncrossed (left) disparity (red filter was in front of the right eye).

3.4 EEG data recording and analysing

Twenty-one active electrodes were placed based on the international 10–20 system, and the average of all active electrodes was chosen as a reference (*see Figure* 5).

The open-source toolbox EEGLAB 2022.1.0 connected to MATLAB R2020a (MathWorks Inc., Natick, MA, USA) was used for EEG data analysis.

Figure 5. The experiment set up and electrodes placement.

4. RESULTS

4.1 Brain activity when viewing anaglyph *versus* volumetric 3D

4.1.1 Performance Data

The mean correct response rates for target-present stimuli were 0.98 (SD = 0.04) on the flat-panel display, and 0.98 (SD = 0.04) on the multi-plane display. The correct response rates dropped to 0.81 (SD = 0.06) and 0.81 (SD = 0.10) when the target-absent stimuli were shown on the flat-panel display and volumetric display, respectively. Two-way ANOVA showed a significant main effect of stimulus condition ($F(1, 19) = 77.5$, $p < 0.001$, $\eta^2_G = 0.664$). The main effect of visualization system (volumetric or flat-panel display) ($F(1, 19) = 0.005$, $p = 0.95$, $\eta^2_G < 0.001$) and interaction ($F(1, 19) = 0.07$, $p = 0.79$, $\eta^2_G < 0.001$) were not significant on response rate.

In addition, response times (RT) were analysed. The mean time was considerably shorter when the visual search arrays were presented on the volumetric multiplanar display than on the flat-panel display (*see Figure 6*). There were significant main effect of visualization system ($F(1, 19) = 17.5$, $p < 0.001$, $\eta^2_G = 0.037$) and stimulus condition ($F(1, 19) = 58.7$, $p = 0.001$, $\eta^2_G = 0.348$). However, there was no significant interaction ($F(1, 19) = 0.12$, $p = 0.73$, $\eta^2_G < 0.001$).

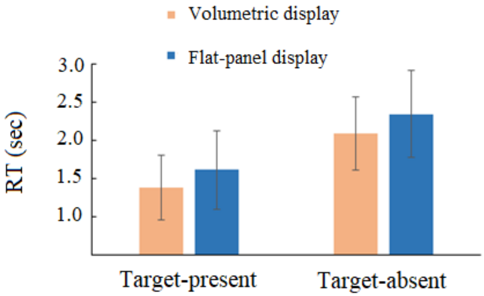

Figure 6. Averaged response times when the feature visual search arrays were presented on two types of display.

4.1.2 Electrophysiological Data

Figure 7 shows changes in amplitudes of ERPs at three time-windows averaged over all subjects when completing the feature search tasks on the flat-panel display and multi-plane volumetric display.

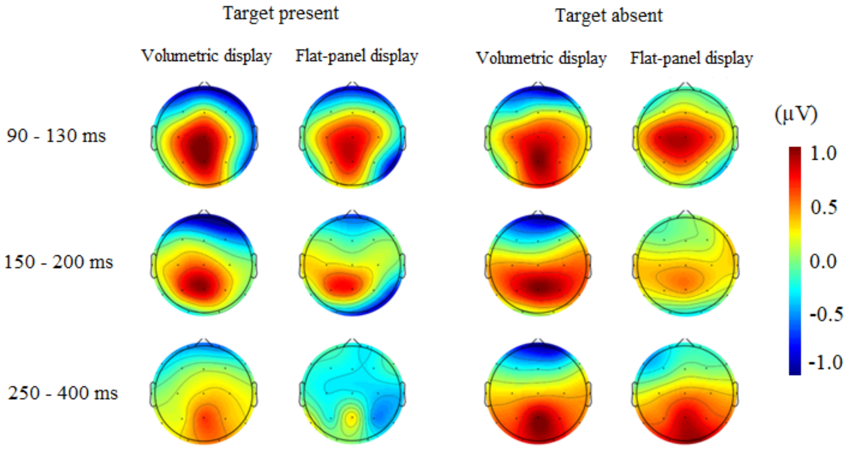

Figure 7. ERP topographical maps reflecting the brain activity during three time-windows, averaged across all.

The ANOVA analysis showed a significant main effect of the stimulus condition ($F(1, 19) = 8.7$, $p = 0.03$, $\eta^2_G = 0.034$) and electrode position ($F(2.0, 38.2) = 10.4$, $p < 0.01$, $\eta^2_G = 0.060$) on the mean amplitudes of ERPs in the time window of the 90–130 ms time after the onset of the visual search array on the display. No significant effect of the visualization system (volumetric or flat display) was shown ($F(1, 19) = 0.04$, $p = 0.84$, $\eta^2_G < 0.001$), and no interactions between factors were proved to be significant. Post hoc Bonferroni adjusted pairwise t-tests did not reveal any major differences when comparing the brain activity across two hemispheres neither for electrodes in the occipital region ($p = 1.0$), nor for the ones in the parietal region ($p = 0.95$).

At the time-window 150–200 ms after the onset of the stimuli, the significant main effects on the mean amplitudes of ERPs were found for the following factors – visualization system ($F(1, 19) = 35.4$, $p < 0.01$, $\eta^2_G = 0.065$) and electrodes ($F(4, 76) = 44.2$, $p < 0.01$, $\eta^2_G = 0.243$). No significant effect of the stimulus condition (target-present and target-absent) was revealed ($F(1, 19) = 0.2$, $p = 0.66$, $\eta^2_G = 0.001$), and no interactions between factors were proved to be significant. Post hoc t-tests showed that the brain activity differed significantly when comparing the mean amplitudes across two displays on

O2 electrode ($p < 0.01$) and P4 electrode ($p = 0.01$), but not on the other three electrodes ($p = 1.0$). Moreover, when comparing the amplitudes of ERPs across two hemispheres separately for each visualization type, a marked asymmetry was revealed in the activity on electrodes positioned in the parietal region when viewing images on the flat-panel display ($p < 0.01$). However, the brain activity was similar in both hemispheres when images were presented on the volumetric display ($p = 1.0$).

Finally, the significant main effects were found for the stimulus condition (target-present or target-absent) ($F(1, 19) = 39.5$, $p < 0.01$, $\eta^2_{\mathrm{G}} = 0.265$) and electrodes ($F(2.5, 48.1) = 12.7$, $p < 0.01$, $\eta^2_{\mathrm{G}} = 0.076$) in the analysis of brain activity during 250–400 ms after the onset of visual search array. Moreover, the interaction between stimulus condition and visualization system was demonstrated as significant ($F(1,19) = 4.6$, $p = 0.05$, $\eta^2_{\mathrm{G}} = 0.028$). The post-hoc analysis of the interaction revealed that the brain activity differed considerably across two visualization systems in the case of target-present images ($p < 0.01$), but not in the case of target-absent images ($p = 1.0$). Specifically, a stereoscopic presentation of the target depth led to larger negative values in the parietal area.

In addition to ERPs, changes on frequency bands were evaluated. Figure 8 plots the average power spectrum of neural oscillations on EEG channels in the parietal lobe and occipital lobe. As seen in figure 8, the power of oscillations was similar for stereoscopic and volumetric images at lower frequencies (alpha band). However, the difference in power grew continuously at higher frequencies (beta band).

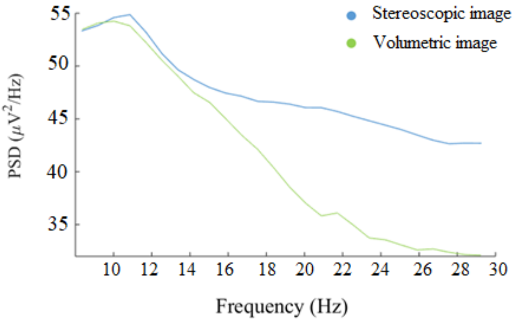

Figure 8. Average power spectrum for EEG channels in the parietal lobe and occipital lobe.

Pairwise comparisons were run using t-tests. Although, no considerable differences were revealed when comparing alpha band power spectrum power on every electrode across two types of three-dimensional visualization ($p > 0.08$) Beta band spectral power was significantly larger on all electrodes ($p < 0.05$), except for Fp2, F3, F4, P4, and Pz, for which the differences did not reach statistical significance (*p* = 0.05). For a closer look, Figure 9 plots the average power of beta band in EEG channels in the parietal lobe and occipital lobe in a comparative manner for stereoscopic and volumetric images (target-present).

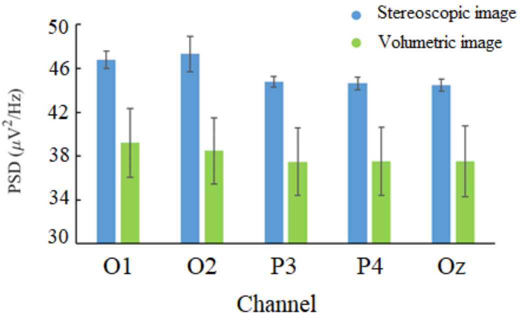

Figure 9. Beta band power spectral density of EEG channels in the parietal lobe and occipital lobe.

4.2 Brain activity: crossed and uncrossed images

Crossed and uncrossed disparity designed based on the anaglyph 3D image to find out if there is any sensitivity of EEG signals to the crossed and uncrossed disparity perception.

4.2.1 Task Performance Data

The behaviour performance data, as depicted in figure 10, illustrates a high rate of correct responses across all participants for both crossed and uncrossed disparities. Specifically, the rate of correct responses is 96.32% for crossed disparity and slightly lower at 94.91% for uncrossed disparity. However, statistical analysis using the Wilcoxon rank-sum exact test (W = 1, *p* = 1.0) did not reveal any significant difference between the two types of disparity.

In terms of response times, the average response time was 2.85 ± 0.05 seconds for crossed disparity and 2.93 ± 0.04 seconds for uncrossed disparity. This indicates a slightly quicker response time for crossed disparity compared to uncrossed disparity. However, like the analysis of correct responses, the statistical analysis of response times using the Wilcoxon rank-sum exact test (W = 0, *p* = 1.0) did not find any significant difference based on the type of disparity presented on a flat-panel display.

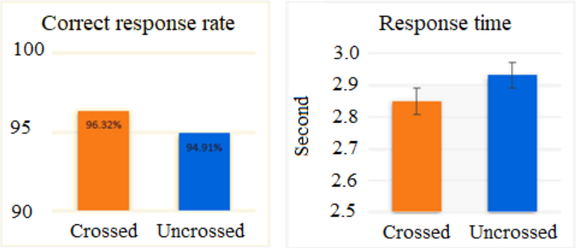

Figure 10. The average correct response rate (left) and response time (right) for crossed and uncrossed disparity present on a flat-panel display.

4.2.2 Event-Related Potentials (ERPs)

The EEG results for both crossed and uncrossed disparity were analysed across three time-windows (50–100 ms, 100–200 ms, 200–500 ms) as ERP components (N1, P2, and P3). The primary brain activity signals during the perception of different disparity were found in the parietal and occipital areas.

In the first time-window (50–100 ms), no discernible difference in brain activity was observed between crossed and uncrossed disparity. Both types of disparity showed activity primarily in the posterior part of the brain.

Moving to the second time-window (100–200 ms), the brain activity was similar for both types of disparities, predominantly located in the parietal region. However, a slightly higher level of activity was noted in the case of uncrossed disparity.

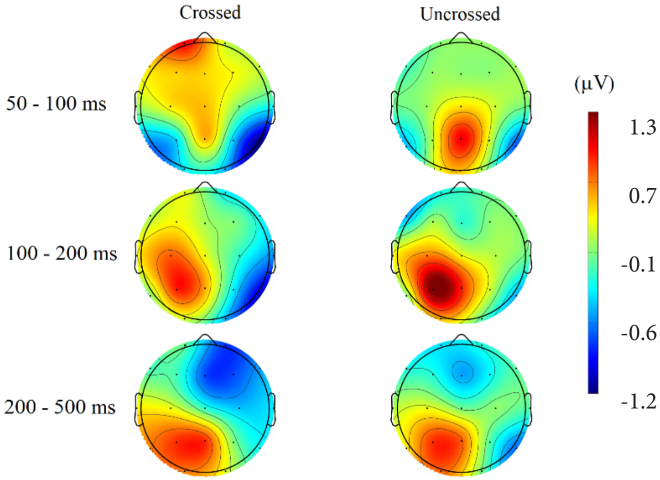

Figure 11. Topographical plots of ERP components in three time-windows for crossed and uncrossed disparities showed on a flat-panel display.

In the final time-window (200–500 ms post-stimuli), the activity was mainly concentrated in the occipital part of the brain, with a slightly higher level of activity observed in the case of crossed disparity (as depicted in Figure 11).

The Wilcoxon rank-sum exact test was employed to analyse the average amplitude of parietal lobe electrodes (P3, P4, Pz) and occipital lobe electrodes (O1, O2) in both crossed and uncrossed disparity conditions. Figure 12 depicts a higher amplitude for the crossed disparity in the N1 component of ERP between 50–100 ms post-stimuli, yet no statistically significant difference was observed (W = 13, $p = 0.04$). Conversely, the P2 component exhibited a significantly higher amplitude during uncrossed disparity between 100–200 ms post-stimuli (W = 32, $p < 0.05$). The amplitude of crossed and uncrossed disparity in the P3 component between 200–500 ms post-stimuli was relatively similar, with no statistically significant difference estimated ($p = 0.08$).

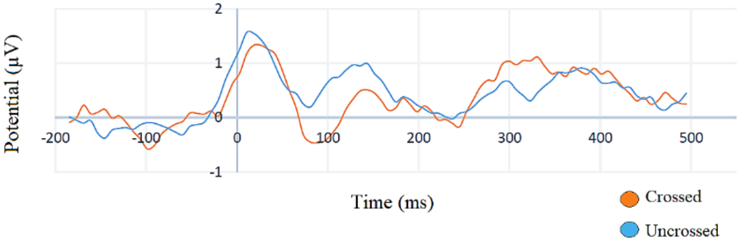

Figure 12. The waveform plots of ERP average of five electrodes (P3, P4, Pz, O1, and O2) for crossed and uncrossed disparities showed on a flat-panel display.

4.2.3 Power Spectral Density (PSD)

The Wilcoxon signed-rank exact test was utilized to analyse theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz) waves. Theta wave activity for both disparity types was predominantly concentrated in the frontal region of the brain, particularly on Fz electrode. A slight increase in activity was observed in uncrossed disparity; however, no significant difference was detected (W = 8, $p = 1$). Alpha wave activity was evident in the parietal and occipital regions of the brain. Statistically, no difference was found (W = 13, $p = 1$); however, there was a slight decrease in activity in uncrossed disparity. Beta waves exhibited greater activity in crossed disparity compared to uncrossed disparity. The activity was primarily located in the frontal regions of the brain, with statistical significance ($p < 0.05$). The illustration of the topographical map and waveform shows in figure 13 (a) and (b) respectively.

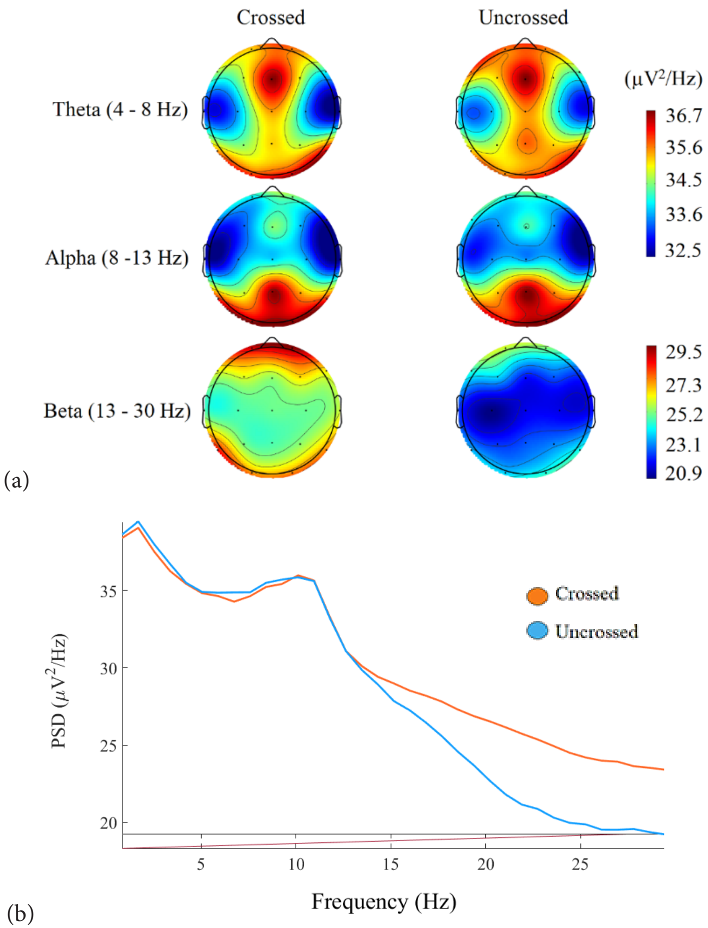

Figure 13. The topographical maps (a) and waveform plots (b) of PSD average of all electrodes across all participants for crossed and uncrossed disparities.

4.3 Brain activity: target-present *versus* target-absent stimuli

4.3.1 Performance Data

The behavioural results indicated that across all participants, the mean correct response rates for 3D stimuli were 0.98 (SD = 0.04); however, more errors were made when individuals responded to 2D stimuli on the volumetric display. Specifically, the correct response rates dropped to 0.82 (SD = 0.06) when the 2D stimuli were shown.

In addition to the correct response rates, Response Time (RT) were analysed to evaluate visual search outcomes. The statistical analysis revealed in figure 14 that there were no significant main effects of the stimulus condition.

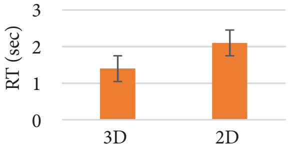

Figure 14. Averaged response times when the visual stimuli were shown on the volumetric display. Error bars depict standard deviations.

4.3.2 Event-Related Potentials (ERPs)

The cortical signals were analysed in three time-windows corresponding to ERPs' N1, P2, and P3 components. Generally, higher activation of occipital and parietal was seen as expected. Figure 15 shows changes in amplitudes of ERPs at three time-windows averaged over all participants in the form of topographical maps. Moreover, figure 16 shows the same time windows in the form of bar chart including information about the standard deviation and *p*-value. As seen in the topographical maps, there is a slightly higher activation in amplitude of the brain signals while responding the 2D visual tasks compared to the 3D targets, however the statistical analysis showed no significantly differences between two types of visual targets. The *p*-value for time-windows 50–100 ms, 100–200 ms, and 200–450 ms were 0.522, 0.267, and 0.272 respectively.

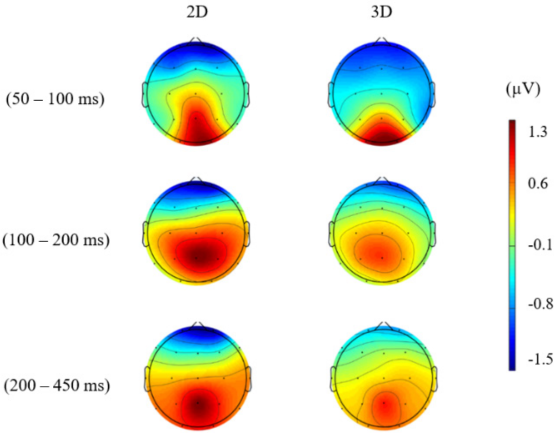

Figure 15. ERP topographical maps reflecting the brain activity during three time-windows, averaged across all participants when performing the 2D task and 3D task on volumetric multiplanar display.

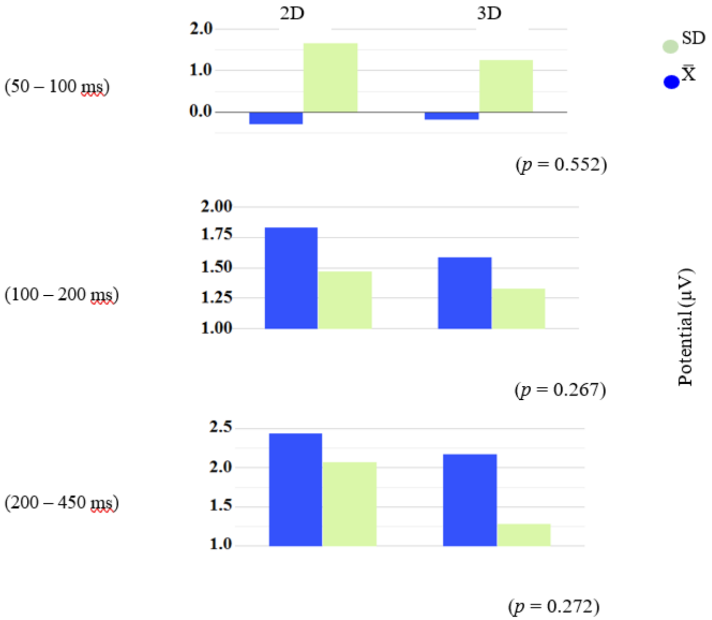

Figure 16. Average and standard deviation of five electrodes P3, P4, O1, O2, and Pz across all participants. P-value represents no statistically significant differences in each time window.

4.3.3 Waveforms

Since the ERPs components are dominant waves on the occipital and parietal areas, the statistical analysis applied on five electrodes (O1, O2, P3, P4, and Pz). Figure 17 indicates the properties of the waveform results. For N1 component, the minimum point of each waveform was considered to perform the statistical analysis. Moreover, the max value of P2 and P3 components were chosen because those are positive deflection. The results showed there was no significant differences between two conditions in three time-windows across all subjects and for each electrode location.

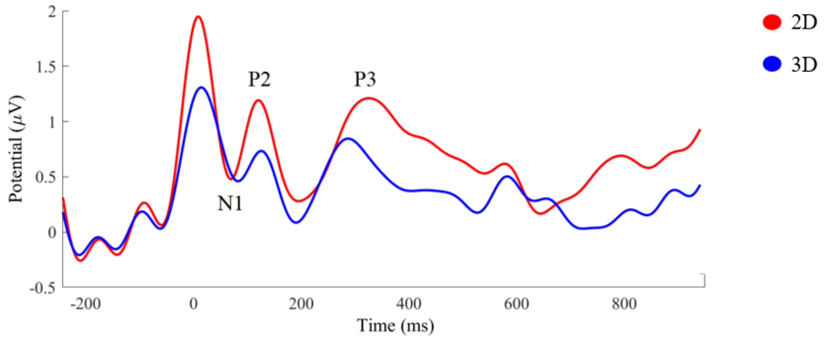

Figure 17. The waveform average of five electrodes O1, O2, P3, P4, and Pz in two conditions (with (3D) or without (2D) depth feature) between –200 to 1000 ms, across all subjects.

The latency analysis of ERP components showed no statistically significant differences between the two visual conditions (target-absent (2D) and target-present (3D)) except for the Pz electrode and within the time-window 200–450 ms, which corresponds to the P3 component. The average latency results are summarized and reported in Table 1.

Table 1. Average latency of N1, P2, and P3 components over five electrodes in two conditions.

Electrodes	50–100 ms			100–200 ms			200–450 ms		
	2D	3D	p-value	2D	3D	p-value	2D	3D	p-value
P3	75.5 ± 18	77 ± 16	0.217	155.5 ± 26	152.5 ± 24	0.701	299 ± 71	309 ± 73	0.677
P4	84 ± 13	85 ± 12	0.796	144 ± 22	138 ± 22	0.421	311 ± 84	322 ± 74	0.711
O1	87 ± 14	85.5 ± 18	0.848	141 ± 27	142 ± 27	0.92	320 ± 70	336 ± 65	0.524
O2	88 ± 11	83 ± 17	0.284	132 ± 22	142 ± 23	0.189	340 ± 55	338 ± 70	0.943
Pz	79 ± 17	73.5 ± 18	0.338	150 ± 27	140 ± 27	0.287	329 ± 68	279 ± 59	0.048

4.3.4 Power Spectral Density (PSD)

Continuous wave analysis showed slightly higher activation in alpha and beta wave frequency bands. However, the difference was not statistically significant. Topographical maps and waveforms of alpha and beta showed in figure 18 (a) and (b), respectively.

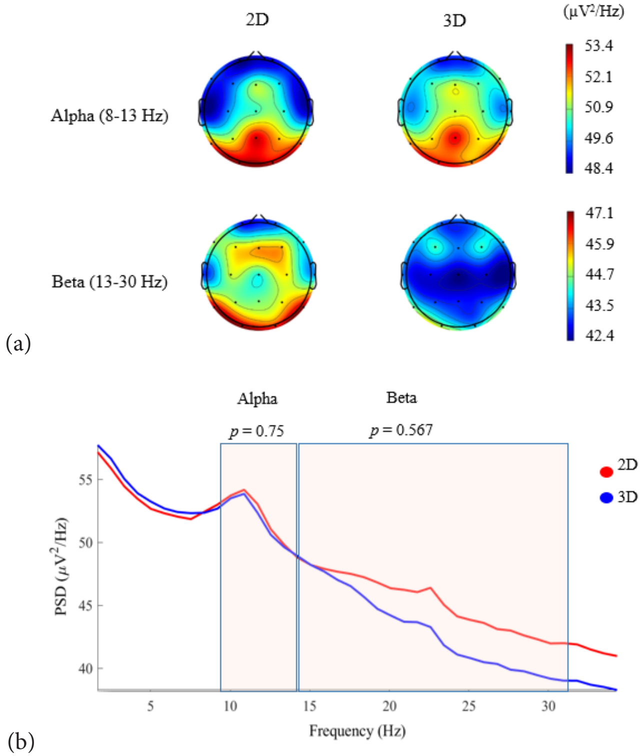

Figure 18. (a) Power Spectral Density (PSD) analysis in the form of the topographical map over the skull average of all participants. (b) The waveform of alpha and beta PSD in wave format. Beta wave shows higher activation in the 2D condition compared to the 3D.

4.4 The impact of different lighting conditions on volumetric image perception

4.4.1 Performance Data

Response Time (RT) was analysed to evaluate visual search outcomes. Two-way ANOVA was used to analyse the first and last experiments in photopic and scotopic conditions. A two-way ANOVA revealed that there was not a statistically significant interaction between the effects of lighting conditions and experiment order (F (1, 26) = 0.016, p = 0.9, η^2_p = 0.0006). Moreover, there was no statistical difference between the first and last experiments (F (1, 26) = 1.264, p = 0.27, η^2_p = 0.05). However, there was a significant difference between photopic and scotopic conditions (F (1, 26) = 10.25, $p = 0.003$, $\eta^2_p = 0.28$). Figure 19 shows the average of each group, showing that in scotopic or low-light conditions, the response time is longer.

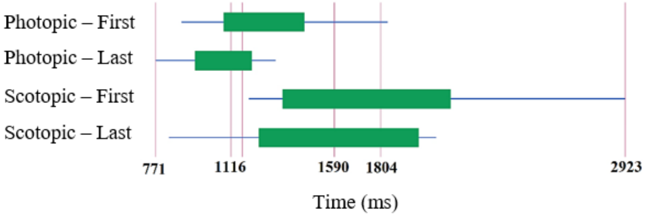

Figure 19. The average response time of participants in each group of lighting conditions and experiment order.

4.4.2 Event-Related Potential (ERP)

An analysis of the raw EEG signal was conducted to extract the peak amplitude and latency of the P3 component of the ERP. The results of ERP analysis are presented in figure 20, which shows the ERP waveforms average of the occipital and parietal regions (O1, O2, P3, P4, and Pz). As expected, the P3 wave was found to be the dominant wave in these regions.

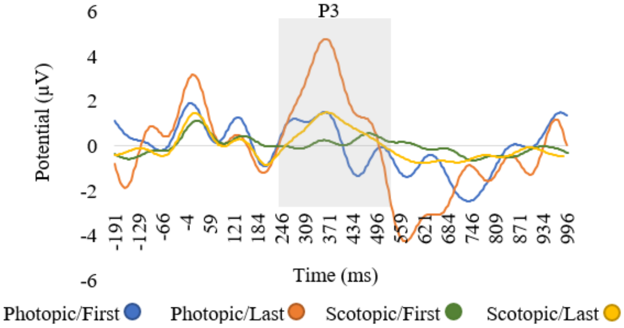

Figure 20. The average of five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) across all participants. P3 peak highlighted on the waveform.

Analysing wave form P3 component, two-way ANOVA showed that there was not a statistically significant interaction between the effects of lighting condition and experiment order (F (1, 36) = 1.571, $p = 0.22$, $\eta^2_p = 0.042$). However, a statistically significant difference was between the first and last experiment

(F(1, 36) = 4.42, $p = 0.04$, $\eta^2_p = 0.11$). Moreover, there was a significant difference between photopic and scotopic conditions (F (1, 36) = 6.23, $p = 0.02$, $\eta^2_p = 0.15$). Figure 21 shows the peak amplitude of each condition.

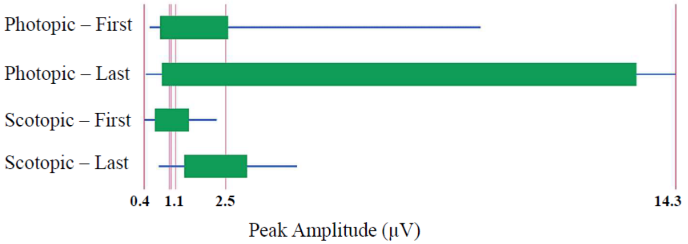

Figure 21. The peak amplitude average of five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) in different lighting conditions and experiment order.

Moreover, about the P3 component peak latency, two-way ANOVA indicated that there was not a statistically significant interaction between the effects of lighting condition and experiment order (F (1, 36) = 2.585, $p = 0.12$, $\eta^2_p = 0.07$). Furthermore, no significant difference between the first and last experiments results (F (1, 36) = 1.17, $p = 0.28$, $\eta^2_p = 0.03$), and no significant difference between photopic and scotopic conditions (F (1, 36) = 1.310, $p = 0.25$, $\eta^2_p = 0.03$).

However, by paired analysis of each lighting condition seperately between the first and last experiment, the paired-t test indicated that there is a significantly large difference between the First (M = 403.5, SD = 75.4) and Last (M = 358.8, SD = 62.4), t(14) = 3.3, $p = 0.007$ experiment in scotopic condition nevertheless, results of the paired-t test in the photopic condition indicated that there is a non-significant small difference between first (M = 346.5, SD = 50.8) and fast (M = 368.4, SD = 40.7), t(14) = 1, $p = 0.367$ experiment. Figure 22 shows the peak latency of P3 component for different illumination conditions and for experiment order.

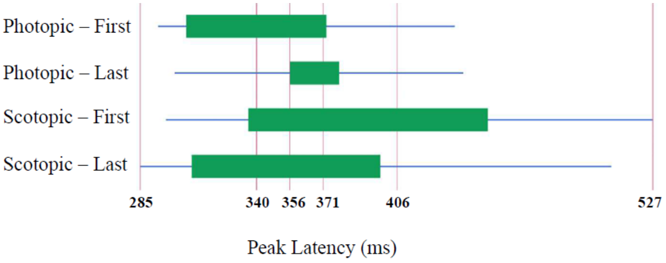

Figure 22. Peak latency of P3 component from five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) in different lighting conditions and experiment order.

5. DISCUSSION

5.1 Brain activity: stereoscopic *versus* volumetric

The results could be interpreted in the context of the cognitive effort required for image classification in three-dimensional visual search. The integration and interpretation of conflicting visual information may impose greater cognitive demands, potentially leading to a faster onset of visual or mental fatigue in the long term [12][13], thereby negatively impacting visual attention and user performance.

Caution should be exercised in interpreting our findings, particularly when considering potential long-term effects. The results were derived from relatively brief task sessions, each lasting approximately 10 minutes. Given that new three-dimensional visualization systems are anticipated to be employed for professional purposes, potentially on a daily basis [14][15], future research should incorporate longer experimental procedures featuring more complex visual scenes.

Another limitation of this study is associated with the experimental design, which involved benchmarking fundamentally different visualization technologies. This approach inherently introduces variability in the technical parameters of displays. While efforts were made to provide participants with similar viewing conditions by matching the relative disparity of search items and adjusting screen brightness levels, it's important to note that the displays had different screen resolutions, and colour filter glasses were only utilized when viewing images on the flat panel display which could reduce the brightness and contrast of the perceived image. Despite these limitations, the current results establish a useful foundation for further research on three-dimensional visual search.

5.2 Brain activity: crossed disparity *versus* uncrossed disparity

Given that crossed and uncrossed disparity are processed by different cortical neurons in the brain [16][17], crossed disparity typically attracts human attention automatically, being a near-located object. However, the same cannot be said for uncrossed disparity. This raises the question of whether this difference is reflected and evaluated in brain activity.

The study did find some differences in brain activity for the P2 and P3 components, as well as theta and beta waves. These differences may be related to the higher attention demand for uncrossed disparity and the better performance for crossed disparity [18][19][20].

The study acknowledges limitations, such as the small sample size and the lack of analysis of gamma waves. Overall, the study provides some insights into how the brain processes different types of depth perception cues, but further research is needed to fully understand these processes.

5.3 Brain activity: target-absent *versus* target-present stimuli on the volumetric display

Shorter response times for 3D (target-present) stimuli, suggesting easier perception [21][22]. Brain activity analysis showed early activity (50–100 ms) in occipital and parietal regions was similar for both stimuli (target-absent (2D) or target-present (3D)), suggesting similar early signal processing [23][24][25][26][27][28][29][30]. P2 component (100–200 ms) showed slightly higher activity for 2D stimuli, potentially due to memory demands in distinguishing stimuli [31][32]. P3 component (250–1000 ms) showed slightly higher amplitude and longer latency for 2D stimuli, suggesting greater difficulty in discriminating 2D stimuli or to consider that the object is not spatial, i.e. a negative answer always takes longer [33]. Alpha and beta band activity (during the entire observation period) was slightly higher for 2D stimuli, potentially reflecting additional processing demands.

Overall, the study suggests that while 3D perception is faster and requires less processing, discriminating between 2D stimuli on a volumetric display might be more challenging compared to 3D stimuli.

5.4 The impact of different lighting conditions on volumetric 3D perception

The results showed that people were faster at the task under bright light, but there was no difference in their speed between the first and last time they did the task under different lighting conditions (photopic and scotopic). This suggests that they may have learned the task and improved their performance over time [34]. The P3 component was larger in the last task compared to the first task, especially under bright light. This suggests that people paid more attention as they learned the task. However, the latency of the P3 component did not change significantly, except in the dim lighting condition, where it became shorter over time. This suggests that using the display in dim light may help people learn the task better [35][36][37].

Overall, the study suggests that lighting and prolonged use can affect how the brain works when using a volumetric display, but the effects are complex and depend on the specific task and lighting conditions.

6. CONCLUSIONS

This thesis investigated how different 3D visualization methods impact the brain and user experience. The study found that the type of 3D display (volumetric *versus* stereoscopic) and image properties (target-absent 2D *versus* target-present 3D; photopic *versus* scotopic conditions) can significantly affect user performance and brain activity. Volumetric image perception was found to be potentially faster process and require less cognitive effort compared to stereoscopic image perception. The research also suggests that EEG is a promising tool for objectively assessing 3D perception. Overall, the thesis provides valuable insights for designing future 3D visualization systems and improving our understanding of 3D perception.

7. THESES

An application of EEG data to examine depth perception objectively has been studied by employing several analytical approaches:

1. The amplitude and latency analysis of both early and late stages of Event-Related Potentials (ERPs) are reliable factors to examine the depth perception objectively since an increase in latency of P3 component of ERP indicates a higher level of difficulty in perceiving the depth either 3D anaglyph or 2D volumetric. Similarly, a higher amplitude of P3 component suggests a greater difficulty in depth perception. In addition, frequency band analysis (particularly the Alpha and Beta bands) is a reliable method for the objective assessment of depth perception since higher power in these bands is associated with increased difficulty in depth perception (P1, P2, P3, P4, C1, C2, C3, C8, C11)
2. The external lighting condition can affect depth perception, therefore, objective assessment of depth perception by EEG and volumetric display should be perform in a dim room to avoid any extra load on the cortical activity. (P2, C3)
3. The sensitivity of EEG in detecting changes in cortical activities when perceiving the depth makes it a reliable tool to assess the depth perception objectively. (P1, P2, P3, P4, all conferences)

8. LIST OF PUBLICATIONS AND CONFERENCES

Publications

P1. **Naderi, M**, Pladere, T, Alksnis, R, Krumina, G (2023). Brain activity underlying visual search in depth when viewing volumetric multiplanar images. *Scientific Reports,* 13, Article Number: 7672, p. 1–9, DOI: 10.1038/s41598-023-34758-9 (Q2).

P2. **Naderi, M,** Abdullayeva, A, Pladere, T, Krumina, G (2023), The Impact of Different Lighting Conditions on the Neural Processes Underlying Relative Depth Perception in 3D Visualization Using Volumetric Multiplanar Display. (IFMBE Proceedings; Vol. 89). *Springer*, P. 172–180. DOI: 10.1007/978-3-031-37132-5_22.

P3. Pladere, T, **Naderi, M**, Zabels, R, Osmanis, K, Krumina, G (2020), Comparative assessment of brain activity during depth perception of stereoscopic and volumetric images. (Proceedings of SPIE; Vol. 11481). Article number 1148108, p. 1–7. DOI: 10.1117/12.2567461 (Q4).

P4. **Naderi, M,** Pladere, T, Krumina, G (2020), EEG based assessment of user performance for a volumetric multiplanar display / Mehrdad Naderi, Tatjana Pladere, Gunta Krūmiņa (Proceedings of SPIE; Vol. 11350). Article number 113500C, p. 1–7. DOI: 10.1117/12.2555646 (Q4).

Conferences

C1. 82nd International Scientific Conference of the University of Latvia, (2024, Riga, Latvia): Quantitative EEG Analysis of Cortical Dynamics during Volumetric 3D Image Perception. **Naderi, M**, Abdullayeva, A, Pladere, T, Alksnis, R, Krumina, G.

C2. 4th International Symposium on Visual Physiology, Environment, and Perception (VisPEP), (2024, Warsaw, Poland): Exploring Visual Ergonomics in Volumetric Multiplanar Displays: An EEG Study. **Naderi, M**, Abdullayeva, A, Pladere, T, Alksnis, R, Krumina, G.

C3. 19th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, (NBC), (2023, Liepaja, Latvia): The Impact of Different Lighting Conditions on the Neural Processes Underlying Relative Depth Perception in 3D Visualization Using Volumetric Multiplanar Display. **Naderi, M**, Abdullayeva, A, Pladere, T, Krumina, G.

C4. International student conference 2023, Rīga Stradiņš University, (2023, Riga Latvia): Visual Neural Facilitation in a Long-Term Visual Search Task on a Volumetric Multiplanar Display: An ERP Study. **Naderi, M**, Abdullayeva, A, Pladere, T, Krumina, G.

C5. 14th International Conference of Lithuanian Neuroscience Association, (2022, Vilnius, Lithuania): EEG Study of Mental Fatigue Regarding

Long-term Usage of Volumetric Multiplanar Display. **Naderi, M**, Abdullayeva, A, Pladere, T, Alksnis, R, Krumina, G.

C6. 18th International Young Scientist Conference "Developments in Optics and Communications 2022", (2022, Riga, Latvia): EEG assessment of disparity-driven brain activity. Abdullayeva, A, **Naderi, M**, Pladere, T, Krumina, G.

C7. 80th International Scientific Conference of the University of Latvia, (2022, Riga, Latvia): EEG Signals During the Perception of Physical and Simulated 3D Images. **Naderi, M**, Pladere, T, Zabels, R, Krumina, G.

C8. 13th International Conference of Lithuanian Neuroscience Association, (2021, Vilnius, Lithuania): Human brain reacts differently to real three dimension (3D) and stereoscopic 3D: An EEG study. **Naderi, M**, Pladere, T, Delesa-Velina, M, Zabels, R, Krauze, L, Musayev, I, Krumina, G.

C9. 43rd European Conference on Visual Perception (ECVP), 2021 (Online): Sensory components of event-related potentials react differently to the perception of volumetric 3-dimensional and 2-dimensional images. **Naderi, M**, Pladere, T, Musayev, I, Krumina, G.

C10. 17th International Young Scientist Conference "Developments in Optics and Communications 2021", (2021, Riga, Latvia): Neural indicators of cognitive load when working with the volumetric multi-plane display. **Naderi, M**, Pladere, T, Krumina, G.

C11. Neuromatch 3.0, (2020, Pennsylvania, USA) (online): EEG signals during relative depth judgments: Effect of image display techniques. **Naderi, M**, Pladere, T, Krumina, G.

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