University of Latvia

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

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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) to evaluate the three-dimensional (3D) visual perception of volumetric images. The EEG-based algorithm aims to assess depth perception objectively and visual ergonomics associated with the volumetric display. Given the novelty of this display, the research contributes valuable information about its interaction with the human visual system, addressing gaps in understanding depth perception and visual comfort.

The brain activity recorded during the 3D visual task performance and then analysed by open-source toolbox EEGLAB 2022.1.0 connected to MATLAB R2020a. Event-Related Potential (ERP) and Power Spectral Density (PSD) were under peer inspections mostly at occipital and parietal area of the scalp in different study design.

The results revealed significant changes in the parietal area of the scalp across all study designs. Notably, the P3 component of Event-Related Potentials (ERPs) exhibited significant differences between volumetric 3D images and images displayed on flat screen by applying anaglyph principle. Additionally, an asymmetry in brain activity between hemispheres was observed in anaglyph, but not in volumetric depth perception.

Power Spectral Density (PSD) analysis indicated significantly higher brain activity in anaglyph compared to volumetric depth perception. Moreover, the study of lighting conditions demonstrated that depth perception on the volumetric display was easier in scotopic conditions.

In conclusion, the dissertation established that EEG is a reliable tool for evaluating the interaction of the human visual system with new technological designs, offering valuable insights into neuroimaging and cognitive task evaluation. This research had implications for advancing knowledge in both neuroimaging and cognitive tasks, highlighting the potential of EEG in uncovering intricate details of human visual perception in response to innovative technological advancements.

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

ANOTĀCIJA

Disertācija uzrakstīta angļu valodā uz 79 lappusēm, kurās iekļauti 40 attēli, 1 tabula un ir atsauces uz 131 literatūras avotu. Disertācijas mērķis bija izstrādāt elektroencefalogrāfijas (EEG) metodes pielietojumu volumetrisko objekta trīsdimensionālās (3D) redzes uztveres izpētei. Uz EEG balstīts algoritms ir paredzēts dziļuma uztveres objektīvai novērtēšanai un redzes ergonomikas novērtēšanai, aplūkojot volumetriskā ekrāna radītos attēlus. Pēdējos gadus volumetriskais ekrāns ir jauna pieeja telpiskā attēla veidošanā, un šis pētījums sniedz vērtīgu informāciju par radītā attēla mijiedarbību ar cilvēka redzes sistēmu, risinot trūkumus izpratnē par dziļuma uztveri un redzes komfortu.

Smadzeņu darbība tika reģistrēta 3D vizuālā uzdevuma izpildes laikā un pēc tam analizēta, izmantojot atvērtā koda rīku EEGLAB 2022.1.0, kas savienota ar MATLAB R2020a. Cilvēka dziļuma uztvere tika pētīta, pielietojot izsauktos potenciālus (Event-Related Potentials) un jaudas spektrālo blīvumu (Power Spectral Density). Šie parametri tika novērtēti galvas smadzeņu pakauša un paura daivās.

Rezultāti atklāja būtiskas izmaiņas galvas tiešajā zonā visos pētījuma dizainos. Jo īpaši notikumu izraisīto potenciālu (ERP) P3 komponente uzrādīja būtiskas atšķirības starp tilpuma 3D attēliem un attēliem, kas parādīti uz plakana ekrāna, izmantojot anaglifu principu. Turklāt anaglifā, bet ne tilpuma dziļuma uztverē, tika novērota smadzeņu aktivitātes asimetrija starp puslodēm.

Jaudas spektrālā blīvuma analīze liecināja par ievērojami augstāku smadzeņu aktivitāti anaglifā salīdzinājumā ar tilpuma dziļuma uztveri. Turklāt apgaismojuma apstākļu pētījums parādīja, ka dziļuma uztvere uz tilpuma displeja bija vieglāka skotopiskos apstākļos.

Noslēgumā darbā tika konstatēts, ka EEG ir uzticams instruments cilvēka redzes uztveres pētīšanai mijiedarbojoties ar tehnoloģiju radītiem attēliem. Šim pētījumam ir ietekme uz zināšanu attīstību gan neirovizuālās attēlveidošanas, gan kognitīvo uzdevumu jomā, uzsverot EEG potenciālu cilvēka redzes uztveres sarežģītu detaļu atklāšanā, reaģējot uz inovatīviem tehnoloģiskiem sasniegumiem.

Atslēgvārdi: elektroencefalogrāfija, volumetriskais displejs, vizuālā meklēšana, dziļuma uztvere, izsauktie potenciāli, jaudas spektrālais blīvums

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List of abbreviations

BCI	brain-computer interface
3D	three-dimensional
VR	virtual reality
AR	augmented reality
EEG	electroencephalography
ERP	event-related potential
PSD	power spectral density
LP	linear prediction
ICA	independent component analysis
STFT	short time Fourier transform
WT	wavelet transform
CWT	continuous wavelet transform
DWT	discrete wavelet transform
μV	micro volt
VEP	visual evoked potential
CLI	cognitive load index
LGN	lateral geniculate nucleus
MOE	multi-planar optical element
RT	response time

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1. Introduction

1.1 Motivation

The brain is a complex network. Neurons of different regions collaborate efficiently to process the obtained data from the entire body. Neural networks integrate information through anatomical and functional connections. All have been discovered by developing Brain-Computer Interface (BCI). Today, brain interaction mechanisms in cognitive tasks are gaining more and more interest. BCI works based on interpreting the mental state by analysing the brain signals. Indeed, a communication system identifies the interaction between the subject and the external world. Therefore, utilizing BCI in different cognitive aspects of the brain is growing.

Moreover, the three-dimensional (3D) displays provide high-quality images resulting a sense of realism with stunning visuals for the audiences by creating the illusion of depth and volume. These displays are designed to provide a more immersive and realistic viewing experience compared to traditional 2D displays. Some common types and technologies associated with 3D displays are available, such as stereoscopic 3D displays, autostereoscopic 3D displays, volumetric displays, holographic systems, Virtual Reality (VR), and Augmented Reality (AR) headsets, although stereoscopic and auto-stereoscopic systems are most commonly used to produce 3D-TV for the public [1].

All we know is the sensation of depth is vivid and enhances the overall user experience. However, in the field of human-computer interaction, the crucial question is whether the depth effect produced by the new methods is beneficial enough to users that perceive depth effect with slightest visual symptoms regarding the accommodation-vergence conflict [2]. Answering this question strongly depends on the properties of the generated visual stimuli by the display and the specifics of human visual perception [3]. Therefore, assessing the ergonomics of three-dimensional visualization systems has become essential in terms of depth perception [4][5].

There are several methods in evaluating 3D display interaction with our visual system in form of subjective or objective, each has its own pros and cons. Among the objective methods, electroencephalography (EEG) is a piece of art which is a powerful neuroimaging technique that measures the electrical activity of the brain and has been extensively used to investigate various aspects of human brain, including perception, cognition, attention, emotion, memory, and action. EEG is the most used technique to capture brain signals due to its excellent temporal resolution, non-invasiveness, and low set-up costs. [6]. Therefore, EEG could be a reliable device to investigate different aspects of human visual system such as objective evaluation of depth perception, visual ergonomic of displays, visual load on mental fatigue, etc. EEG was a core of the current study to research its application in depth perception objectively specially when looking on a new generation of 3D displays called volumetric multiplanar display.

Because of novelty of the display, there are lack of enough information regarding the human visual ergonomic conditions. Therefore, the topics of this thesis could provide useful information about the interaction of the volumetric display with human visual system and depth perception.

1.2 Structure of the thesis

1.2.1 Aim

The objective assessment of human visual system function is the one of valuable methods that we can get the results without any bias compared to subjective methods. EEG evaluation of volumetric multiplanar 3D image perception is a novel method studied in this thesis. The aim of the thesis was to study an electroencephalography application that could monitor brain activity while individuals perceive a three-dimensional image displayed on a volumetric multiplanar display. To achieve the goal, we considered the following objectives and hypothesis.

1.2.2 Objectives

The following plan was set to achieve the aim:

1. to evaluate the behavioural data regarding using volumetric multiplanar display.
2. to analyse Event-Related Potential (ERP) components as well as Power Spectral Density (PSD) connecting with sensation, attention, and perception phases to find any impact regarding volumetric display usage and compare it to another 3D as anaglyph.
3. to evaluate the effect of external conditions for example, illumination and task repetition on the cortical activity while performing task on the volumetric display.
4. to study the application of EEG for objective evaluation of depth perception.

1.2.3 Hypothesis

Given that EEG is a highly sensitive tool for analysing temporal resolution, there is significant potential to explore the attentional and perceptual phases of depth perception. 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, as represented by continuous frequency bands, might also be affected in a way that there is higher brain activity in stereoscopic anaglyph over volumetric display. Furthermore, it was hypothesized that task performance on a volumetric display might be less efficient in an illuminated space compared to a dark space.

1.3 Contribution of the author and scientific novelty of work

The author of this thesis studied on the development of an objective method to evaluate depth perception by using brain data analysis recorded via EEG during actual 3D image perception as a volumetric 3D and stereoscopic 3D as anaglyph in different experimental conditions for instance, lighting conditions and workload.

During the doctoral thesis, the author actively participated in all research phases, from designing and executing experiments to processing results and other methodological tasks.

The author autonomously devised the methodology and conducted all experiments, as well as analysed the recorded brain signals. The author took the lead in executing all experiments, processing results, and formulating conclusions.

The thesis can be considered as a novel method since there has not been any objective method to evaluate the depth perception. The current methods mostly centred on the subjective style, which is not free of bios and guessing. Moreover, subjective methods are designed based on binocular disparity depth cue while we use many other depth cues to perceive the depth. By recording and analysing the brain data while perceiving a 3D image contains more than one depth cue, the ability of depth perception can be evaluated objectively and closer to the reality. Although there might be some cons regarding the new method, however, it can be a useful method to evaluate the depth perception, furthermore, discover the underlying processing of different types of depth perception as global and local.

The author of this thesis is a main author of three publications related to the topic of this work and a co-author of one related publication indexed in Scopus and Web of Science. Full list of publications can be found in section 8. The author was supervisor of two defended bachelor’s thesis connected with the application of the EEG method to the study volumetric 3D image perception. In addition, the author was a scientific advisor of a master’s thesis related to application of EEG in detecting depth perception anomalies.

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, therefore in the literature review, firstly, the brain oscillation and its properties was covered, after that the human visual perception and specifically depth perception is discussed and at the end, the structure of a 3D volumetric multiplanar display was studied.

2.2 Brain oscillation

Brain oscillations are activity of central nervous system in form of rhythmic or repetitive pattern. For the first time, Hans Berger reported the electrical activity of human brain by placing electrodes on the surface of the scalp, amplifying the signals, and plotting the signal fluctuations over time in 1929. Later, by developing signal analysis methods, the characteristics of the brain oscillation have been discovered more and more.

2.2.1 Characteristics of oscillations

Generally, every oscillation can be defined by:

1) Amplitude refers to the maximum displacement or distance moved by a point on a vibrating body or wave measured from its equilibrium position. In simpler terms, it is the "size" of the oscillation.
2) frequency, the number of oscillations or cycles per unit of time. It is often measured in Hertz (Hz), which means cycles per second.
3) Phase, a measure of the position of a point in its cycle relative to a fixed point in time. It is often expressed in degrees or radians (see figure 1). Brain oscillations are continuous waves that amplitude is defined by the excitation of neurons. It means, the higher the peak, the more neurons are synchronously active. The amount of amplitude can be up to 10mV on the surface of the brain, however, this number decreases significantly to up to 100μV on the surface of scalp [7].

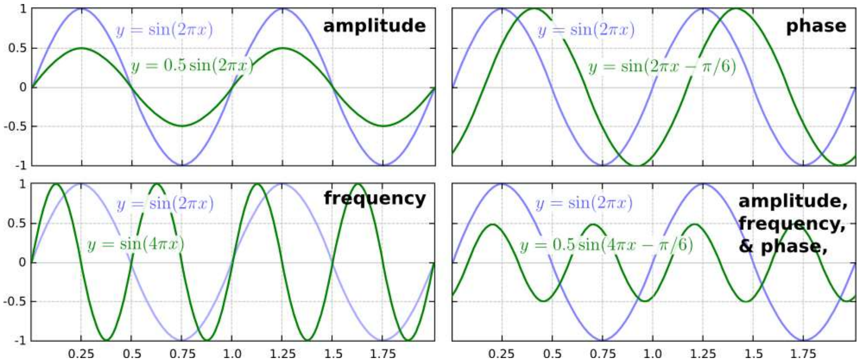


Figure 1. Characteristics of the wave [8].

2.2.2 The main frequency bands of oscillations

EEG signal analysis is a complicated process that is divided into two main phases: (a) pre-processing that contains purifying the raw signal from artefacts by applying artefact removal and data filtering algorithms, and (b) post-processing that contains feature extraction and classification of the recorded signal (see figure 2 and 4). The main purpose of the feature extraction is not only to reduce the signal dimensionality and size, but also to extract more valuable information that hidden in the signals while avoiding unnecessary information. Since EEG signals are nonstationary, non-Gaussian, and have non-linear nature, various techniques can be used for the signal analysis such as: time domain, frequency domain, time-frequency, and non-linear methods [9][10].

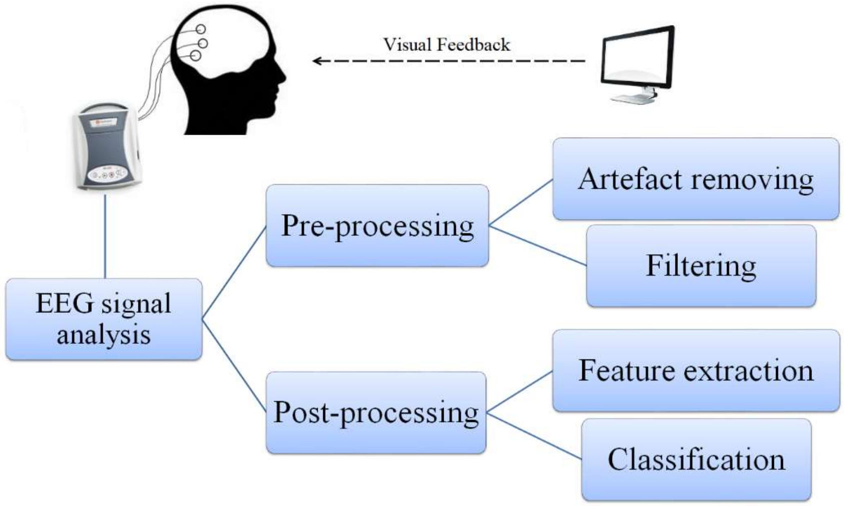


Figure 2. Common BCI functional architecture.

Time domain

Two important methods in time domain analysis are Linear Prediction (LP) and Independent Component Analysis (ICA). LP refers to prediction of output based on the input *x(n)* and previous output *y(n)* values. Formula (1) represent the calculation of linear prediction of time domain analysis.

$$\hat{y}(n) = \sum_{k=1}^{p} a(k)y(n-k) + \sum_{k=0}^{N} b(k)x(n-k) \qquad (1)$$

ICA effectively create a filter that cancel out all other signals except the signal that we want. In ICA, we decomposed the independent signals from a measured signal that is assumed to be linear combination of those independent signals. Formula (2) is the definition of ICA analysis. It is an effective technique to remove artefacts and extracting spatial sources of brain signals from EEG.

$$x_i = a_1 s_1 + a_2 s_2 + \cdots + a_n s_n \qquad (2)$$

Frequency domain

It is the same as the spectral analysis which is a standard and powerful method for EEG data analysis. Power Spectral Density (PSD) is estimated by Fourier transformation of the estimated autocorrelation sequence ($R_x(\tau)$) from a given data set. Formula (3) illustrate the calculation of frequency domain analysis.

$$S_x(f) = \int_{-\infty}^{\infty} R_x(\tau) e^{-2j\pi f\tau}\, d\tau \qquad (3)$$

Figure 3 effectively illustrates the concept of time domain and frequency domain in a visually appealing manner.

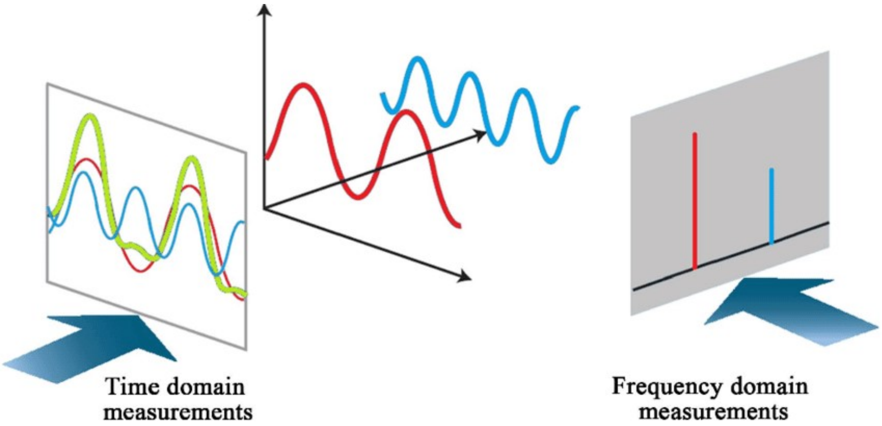


Figure 3. Comparing Time and Frequency Domain Analysis [11].

Time-frequency

Since EEG signals are nonstationary, time-frequency analysis, allow us to study changing of frequency characteristics over time. To achieve this, Short Time Fourier Transform (STFT) and Wavelet Transform (WT) were developed. In STFT which is a conventional way to time-frequency analysis, because the signal divided into small segments (because stationary signals are needed) there are some finite length windows. If the window is narrow, the frequency resolution is poor while the temporal resolution is much better. On the other hand, if the window is wide there is the reverse situation; good frequency resolution and poor temporal resolution [7]. The definition of STFT is shown in formula (4):

$$STFT_x^{(w)}(t,f) = \int_{-\infty}^{\infty}[x(t).w(t-t')]e^{-2j\pi f\tau}\,dt \qquad (4)$$

The WT differs from other transforms, like the STFT, by providing information about the frequency content of a signal as it varies over time. In the STFT, you get information about the frequency components in the entire signal, but you lose the time information. In contrast, the WT allows you to analyse the signal at different time scales, which is valuable for capturing transient or localized features. There are different types of WT, including the Continuous Wavelet Transform (CWT) and the Discrete Wavelet Transform (DWT).

The CWT of a continuous signal f(t) with respect to a wavelet function ψ(a, t) is defined in formula (5):

$$CWT\,(a,b) = \int_{-\infty}^{\infty}[f(t).\psi*(a,t\ -\ b)]\,dt \qquad (5)$$

CWT(a, b) is the CWT coefficient at scale 'a' and translation 'b'.

f(t) is the original continuous signal.

ψ*(a, t - b) is the complex conjugate of the wavelet function ψ(a, t) [7] [12].

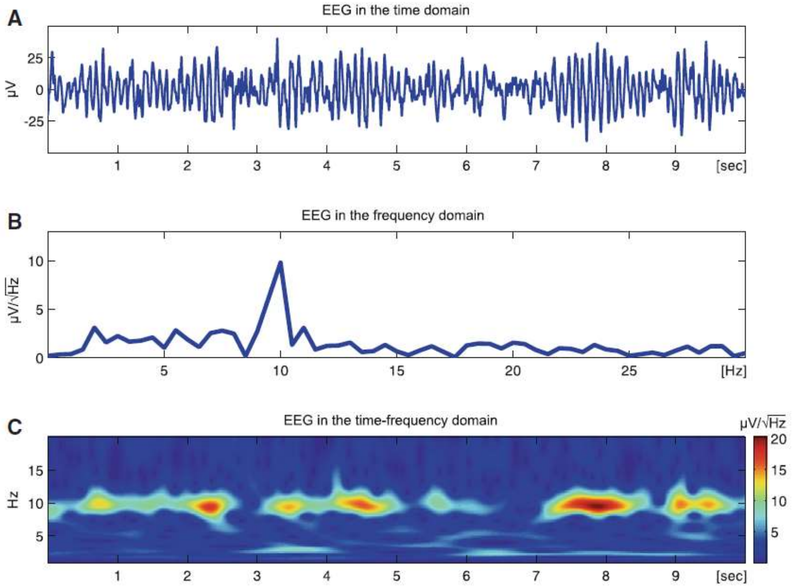


Figure 4. An example of A) time domain, B) frequency domain, and C) time-frequency analysis [13].

Nonlinear methods of analysis

This technique analyses the signals in more efficient way and more complicated, for instance higher order spectra, phase space plot, fractional dimension, etc. that are beyond this thesis.

Brain wave frequencies that result from frequency domain analysis, have a range between 0.5 to 100 Hz that are classified into five groups called Delta, Theta, Alpha, Beta, and Gamma. In different neuroscientific studies, brain frequencies analysed for expressing different purposes, for instance, evaluating pleasure and displeasure state [14], mental fatigue in different situations [15][16][17], 3D image perception [18][19][20]. Moreover, frequency patterns change significantly between sleep and wakefulness state [21].

Delta frequency lie within the range of 0.5 - 4 Hz with amplitude less than 100μV. This wave occurs during deep sleep, infancy, and serious organic brain diseases. Delta oscillation is dominant at the parietal lobs. In visual search studies, delta frequency is studied rarely because it is not regarding the alert state of human perception. Only a few studies analysed delta bands to evaluate any changes before and after virtual reality experiences [22], finding any differences between 2D and 3D displays usage [18][20], and mental fatigue assessment [15]. In almost all of them, there were no statistically significant changes in delta frequency bands.

Theta frequency range between 4 to 8 Hz and like delta wave with amplitude of less than 100 μV. The occurrence situations are sleeping state in adults, wakefulness in children, and during emotional stress in some adults. The regions of dominancy are parietal and temporal lobes. Theta frequency has been studied more than delta band in visual search studies. The role of theta frequency is associated in learning, memory, and spatial memory in animals [23][24]. In different studies theta showed different behaviour, for example, in mental fatigue studies theta had no changes [15][22], or increased after visual load [17], however, in visual effort study, theta showed less power in 3D compared to 2D image perception [25].

Alpha frequency range between 8 and 13 Hz with amplitude less than 10μV. It is dominant wave in occipital region and can be found in normal people who are awake with closed eyes. Alpha band is connected mostly to different states of attention, therefore, in many visual search studies, especially those that centred on attention, alpha has the main role. It means that by increasing the alpha power there will be decreasing the level of attention. Moreover, alpha strongly correlated with working memory. Nowadays, alpha is regarded as the most important oscillation in understanding cognitive processes [26]. In the most of studies regarding mental fatigue due to visual task performance, alpha band increased significantly then result in decreasing attention in participants [15][17] [22].

Beta frequency lie within the range of 13 - 30 Hz with maximum amplitude of 20μV. It is dominant wave on over the middle frontal gyrus. Beta wave appears during intense mental activities, conscious thought, and logical thinking. In optimal conditions, beta waves help with conscious focus, memory, and problem solving. Beta frequency band varies in different visual search studies depend on the visual task load on the cognitive processing. For instance, in one head-mounted virtual reality study beta band over posterior part of the brain increased [22], however in another study related to mental fatigue assessment beta band decreased [15] while in another mental fatigue measurement study there were no changes in beta activity [17].

Gamma frequency range between 30 and 100 Hz with amplitude up to 20μV. Gamma waves are associated with various cognitive functions and are often linked to heightened mental activity often work in conjunction with other brainwave frequencies, such as alpha, beta, delta, and theta waves, to support overall brain function and cognition. Since gamma wave related to complicated problem solving, in most of visual search studies gamma band was evaluated in general format and not in details because most of the visual stimuli designed for the visual search studies are not so complicated, therefore in most of them Gamma band had no significant changes.

In the figure 5, different properties of the brain frequency bands were shown.

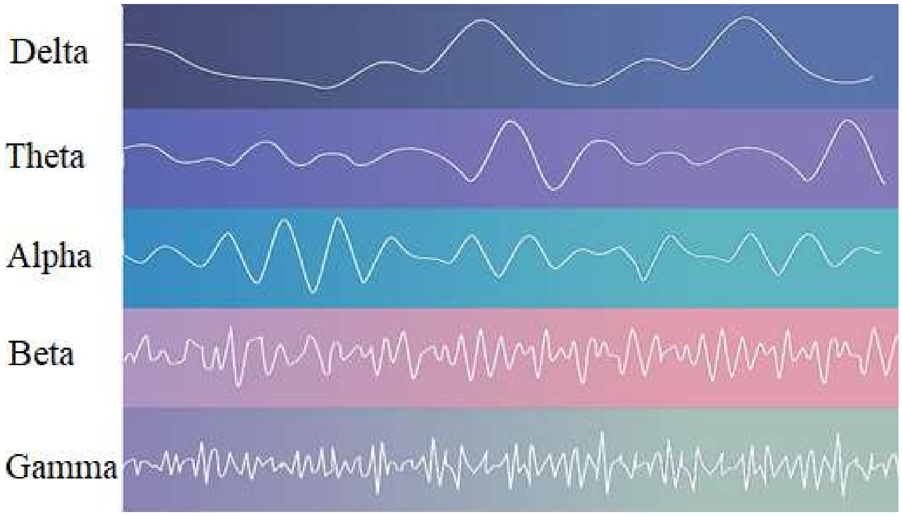


Figure 5. The main category of the human brain frequency bands [27].

2.2.3 The function of brain oscillations

Neural cells anatomy

Although neurons have variety of shapes, however, all have almost the same structure. Each neuron composed of four main parts: A large cell as body; several short branches that get neural message from the other neurons as dendrites; a single long axon that send the message to other neurons; and terminal branch of axon called telodendrion. (See figure 6)

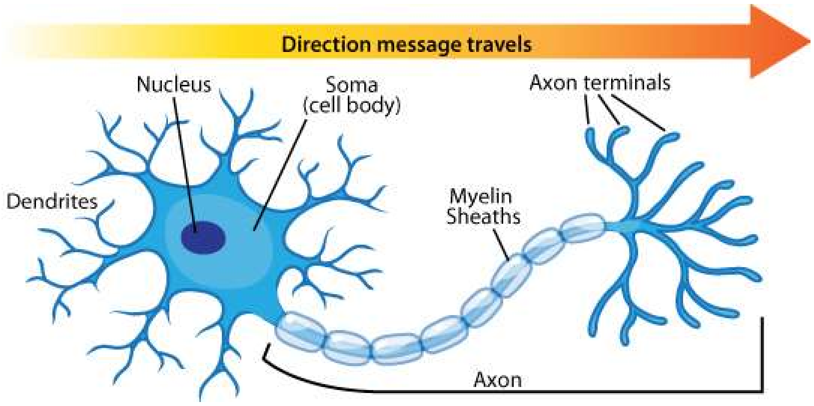


Figure 6. Details of neuron structure and directional movement of neural message [28].

Action potentials

Action potentials or nerve impulses or nerve messages, are defined as the basic functioning of the nervous system communications. Indeed, action potentials are rapid and transient changes in the electrical charge of the cell membrane. An action potential is speared along the surface of an axon and does not diminish when moves away from its source. This allows for the long-distance transmission of signals through the nervous system. The stimulus threshold must be reached to initiate an action potential. The resting membrane potential usually is around -70 mV. This potential is kept by the activity of ion channels. As soon as a signal threshold reaches a critical potential (typically around -55 mV), depolarization occurs, and an action potential begins. This depolarization is a result of voltage-gated sodium channels opening in response to the stimulus. In figure 7, the steps of generating an action potential have been shown.

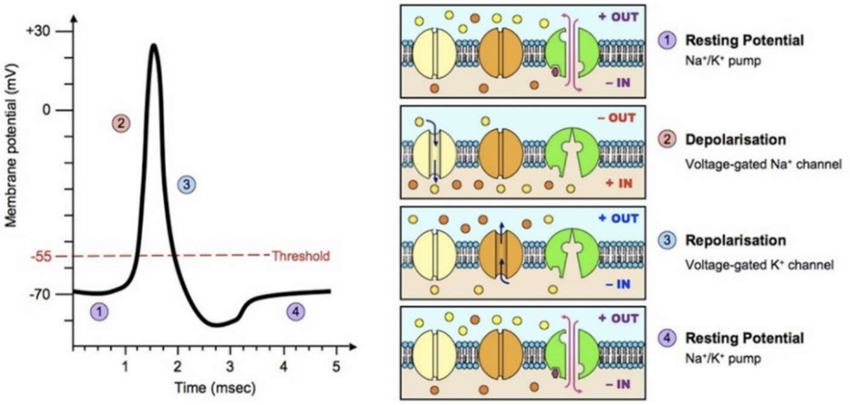


Figure 7. Changes in the membrane potential at one location during the generation of an action potential [29].

Every action potential is considered as a message that propagate through a neural pathway. This message is relayed from one location to another in a series of steps. Infect, there is a repeated message at each step. The message propagation occurs in two ways depends on the axon's type (myelinated or unmyelinated). Figure 8 shows the message propagation in two different ways.

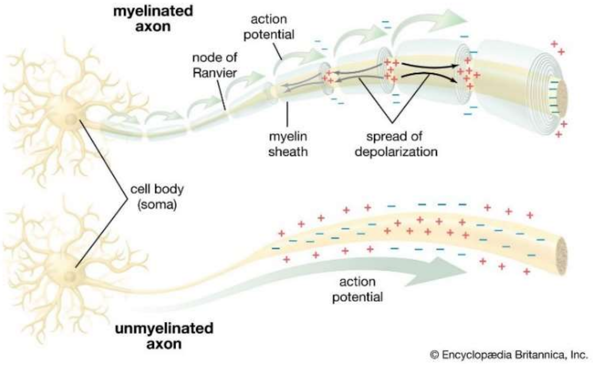


Figure 8. Propagation of action potential in two different axon types [30].

2.2.4 EEG studies on the visual system

EEG is a valuable tool in studying the visual system. By measuring the electrical activity of human brain, various aspects of visual search processing such as perception, attention, memory, and response selection can be investigated. Some key areas that EEG has the main role are: Visual Evoked Potential (VEP), visual attention and perception, colour processing, and memory processing.

VEP indeed tests the integrity of the visual pathways from the eyes to the brain. It is often employed to diagnose and monitor conditions that affect the visual system, such as multiple sclerosis, optic neuritis, and other neurological disorders. By analysing the recorded signals and extracting the specific components of the brain's response to the visual stimulus, any abnormality in the visual pathway is diagnosed. Abnormalities in VEP results, consist of delayed or reduced responses to the visual stimuli.

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 [19].

Marsel Fazlyyyakhmatov and colleagues 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 [31].

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 [32]. 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 [33].

There are massive studies in vision science that collect data via EEG. However, covering all of them is impossible. In the following, structure of an EEG study was reviewed.

Structure of an EEG set-up

EEG data acquisition is done by placing special electrodes on the scalp skin. A committee of the International Federation of Societies for Electroencephalography and Clinical Neurophysiology proposed a specific electrode placement system for use in all laboratories under standard conditions. Their recommendation gave rise to what we now know as the International 10-20 system. However, there are some more standards based on the number of electrodes which placed on the scalp known as 10-5, 10-10, and 10-20 systems. For example, a 10-20 system has a total of 21 electrodes, with 10% and 20% distances along the sagittal and coronal central reference curves. If these midlines are divided into 10%, we get a 10-10 system with 81 electrodes. Finally, adding resolution with distances of 5% results in the 10-5 EEG system with 320 electrodes. Indeed, this system defines the surface locations on the head in terms of relative distances between specific cranial landmarks on the scalp [21]. The "10" and "20" in its name signify that the actual distances between adjacent electrodes are either 10% or 20% of the total front-to-back or right-to-left distance of the skull. This rule can be distributed to other layouts. The system comprises 21 active electrodes, and their placement is illustrated in figure 9.

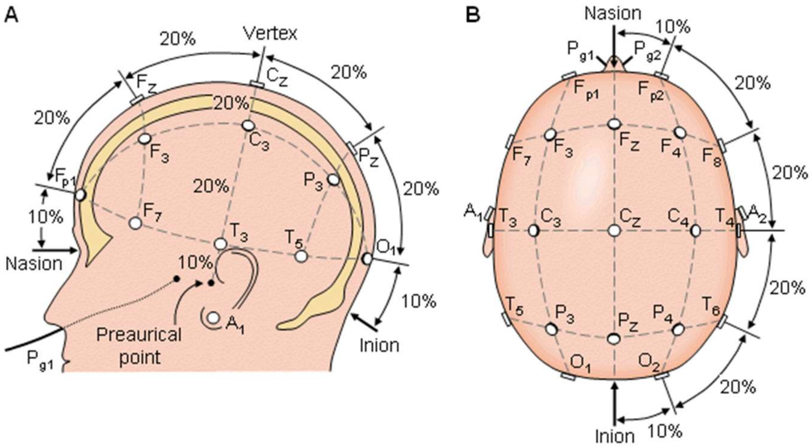


Figure 9. The international 10-20 system seen from (A) left and (B) above the head [34].

The positioning of electrodes on the scalp also known as montage. There are two types of montage: 1) referential montage 2) bipolar montage. In referential method, each electrode records the signals compared to the reference electrode. In bipolar method the measured potential is the difference between two paired active electrodes on the scalp [35]. Collected signals by the electrodes, recorded by an amplifier. It amplifies the weak electrical signals to make them more measurable and suitable for recording. The amplifier also filters out unwanted noise and artefacts to ensure the quality of the EEG signal [36].

Data analysis

Data analysis categorized in four main parts:

1) Pre-processing: includes digitizing the analogue recorded EEG signals at an appropriate sampling rate. Sampling rate allows us to change the accuracy of signal analysis in the way of higher sampling rate results in higher accuracy, but much signal processing is needed. On the other hand, low sampling rate result in less accuracy and in case of very low sampling rate, missing a lot of useful information. The next step is filtering to remove noise and artifacts. Artifacts can be created by head motion or blinking during signal acquisition or issue in electrode connection between EEG amplifier and scalp or physical damage of electrodes. Afterward dividing the data into epochs or segments to extract Event-Related Potentials (ERPs)[35].
2) Feature extraction: it is an important step in EEG data analysis includes time domain, frequency domain, time-frequency analysis, and ERP analysis that all have been explained in previous chapter.
3) Visualization: includes all plots, waveforms, and topographic maps to visualize the distribution of activity across electrodes.

4) Statistical analysis: Performing statistical tests for instance, t-tests or ANOVAs to assess differences in EEG features between conditions or groups.

Event-related Potentials (ERPs)

Event-Related Potential (ERP) represents an averaging technique used to extract specific responses to sensory, cognitive, or motor events and are characterized by a series of distinctive voltage fluctuations in the EEG signal. These fluctuations are time-locked to the occurrence of an event or stimulus, The fluctuations occur at specific points in time after the event. ERP is a valuable tool for studying the brain's processing of various stimuli and cognitive functions [37].

The first clear sensory ERP recording from an awake human was achieved in 1935-1936 by Pauline and Hallowell Davis. The ERPs hidden in raw EEG signal that contaminated by noises in individual trials, can be isolated by signal averaging from the noisy EEG. Increasing the number of trials in the average reduces residual EEG noise, enhancing the signal-to-noise ratio. Thus, it is crucial to include an adequate number of trials in ERP averages [38]. The minimum number of events or trials required for a consistent ERP analysis is 70 trials [39].

The analysis of ERP plays a significant role in visual cognitive research, with scientists typically investigating two key factors: the amplitude of the ERP wave and its latency. Amplitude reflects the number of neurons firing in response to a stimulus, while latency indicates the time it takes for the brain to respond to a stimulus [40].

The ERP waveform on the scalp displays a sequence of positive and negative voltage deflections that vary in polarity, amplitude, and duration over time. Although the peaks are visually noticeable, it is incorrect to assume that each peak corresponds to a specific brain process. Researchers often mistakenly equate a peak in the observed ERP waveform with an underlying ERP component, but it is the underlying components that directly reflect the neural and psychological processes under study [37][39].

To clarify the relationships between the ERP waveform and its components, it is important to establish clear definitions. The observed ERP waveform can be defined as a representation of changes in scalp-recorded voltage over time that reflecting sensory, cognitive, and motor processes triggered by a stimulus. Indeed, an ERP component can be defined as a scalp-recorded voltage change that specifically reflects a distinct neural or psychological process [39].

ERPs in the human brain are categorized into two groups: early waves, peaking sharply within the first 100 milliseconds after a stimulus, known as "Sensory" or "Exogenous," which depends entirely on the physical properties of the stimulus such as size, shape, colour, and intensity. The later components relate to how the subject evaluates the stimulus and are termed as "cognitive" or "endogenous" [37]. Most components are denoted by a letter (N/P) indicating polarity (negative/positive), followed by a number indicating latency in milliseconds. For example, P300 refers to a positive peak occurring around 300 milliseconds after stimulus onset [41]. Figure 10 well illustrates the different ERP components.

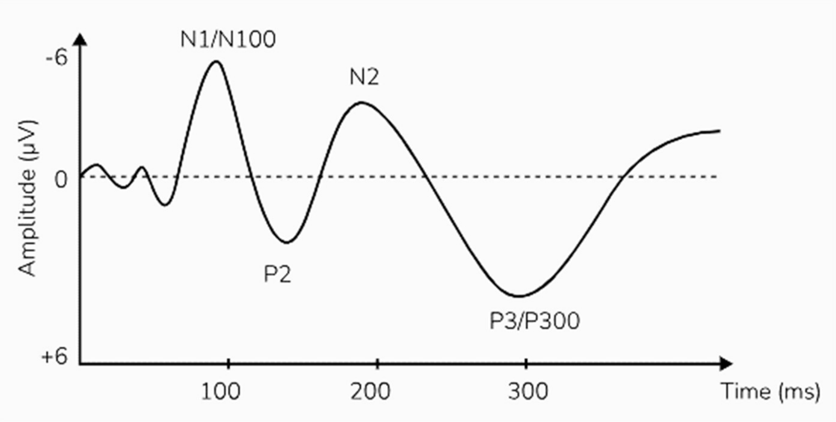


Figure 10. ERP components deflections and latencies. The vertical vector is reversed (minus is upside) [42].

Major ERP components

ERP components represent the perceived status of stimuli well. Since ERP analysis has an excellent temporal resolution, understanding of timing phases of stimuli perception is one of the important advantages of ERP. Some cognitive components happen before individuals making decision or action; therefore, it is valuable to use this feature as an objective assessment of visual ability for example, depth perception because it will be free of bios and guessing.

C1: the first major ERP component that connected to the visual system and it is the dominant wave at posterior midline electrode location. Unlike the other component, it is not labelled as N or P because in different types of visual stimuli, C1 shows different behaviour, either P or N. C1 usually onsets 40-60 ms post-stimuli and peaks 80-100 ms post-stimuli. C1 as an exogenous component is highly dependent on the physical properties of the stimuli such as size, contrast, and shape. Sometimes the amplitude of C1 is too small to be detected [43].

P1: the next component after C1 is P1 which onsets about 90 ms after the stimuli and peaks between 100-130 ms. P1 is the dominant wave at the lateral occipital location. In [44], they showed higher amplitude of P1 when looking at a 2D image with 3D effect compared to the 2D image without 3D effect. This shows the P1 behaviour well about the stimuli dimensions.

N1: the first negative deflection usually peaks 100-150 ms after visual stimuli onset and it is dominant wave at anterior electrode sites but arising from parietal and lateral occipital area. Studies have illustrated that N1 is influenced by some level of spatial attention [38][45].

P2: this component is mostly connected to the attention at the targets which are not so complicated and has a highest amplitude if the target is infrequent. P2 peaks at about 200-250 ms after the stimuli onset and involved in some level of memory performance [44].

N2: like P2, N2 is large for less frequent targets. N2 peaks about 220 ms after the stimuli onset. The location and the latency strongly depends on the stimuli type [43].

P3: the most important component of ERP has been studied vastly in different neuroscientific studies. P3 usually peaks between 250-500 ms after stimuli onset and it is dominant on central parietal site of the scalp. P3 is mostly responsible for the post-perceptual evaluative processes such as attention, cognition, decision making, learning, and conscious perception [46][47]. However, the main responsibility of P3 is still unknown. In [48] Friedman., et al, showed that P3 could be a sign of the brain's evaluation of novelty. Usually, scientists mention P3 amplitude is larger for less probable stimuli however, it is not a single factor relevance. For instance, P3 amplitude will be smaller if the subject is uncertain about the response on the task. In addition, if the task is more complicated and has extra load on the brain then P3 will appear with higher amplitude [38]. The effect of aging on P3 has been studied by [49]. They showed that P3 has large peak on the posterior site in young age however, with increasing age, P3 decreased in amplitude at the posterior sites and increased in amplitude at more frontal locations.

Based on the beneficial attributes of ERP components and the broader advantages of EEG brain signal analysis, exploring the interplay between the human visual system and emerging technologies like volumetric displays could provide valuable insights into the fundamental processes of image perception, particularly depth perception. This is due to the considerable potential for applying brain signal analysis in this context.

2.3 Visual perception

The brain's ability of receiving visual signals from the stimuli, interpret them and responding a proper action defined as visual perception. The process of visual perception involves a sequence of neural signal transformations, occurring in the retina, area V1, and the extra-striate cortex, which ultimately generate patterns of activity that encode the information such as chromaticity, movement, detail, form, and depth, required for recognizing objects, determining their location, and guiding our actions [50]. The first important step in understanding the visual perception is anatomy and biophysics to know and determine the flow of information and processing at various levels.

2.3.1 Biophysics of visual perception

Visual perception is a complex process involves several biophysical mechanisms, from the light capturing by photoreceptor cells to the visual information processing in the brain. In the following, the entire visual processing was discussed.

Retina

There are two types of photoreceptor cells in retina: rods and cones. Cones are responsible for colour vision and are sensitive to different wavelengths of light, while rods are more sensitive to mesopic conditions. Photoreceptor cells contain pigments, such as rhodopsin in rods and various cone pigments that can absorb photons of light. When a photon is absorbed by a photoreceptor, a biochemical reaction happens and finally result in changing in the cell's membrane potential. The electrical signals generated by photoreceptor cells are then transmitted to the bipolar cells and ganglion cells in the retina. These neurons process the visual information before sending it to the brain via the optic nerve. Figure 11 illustrates the retinal layers and photoreceptor cells [51].

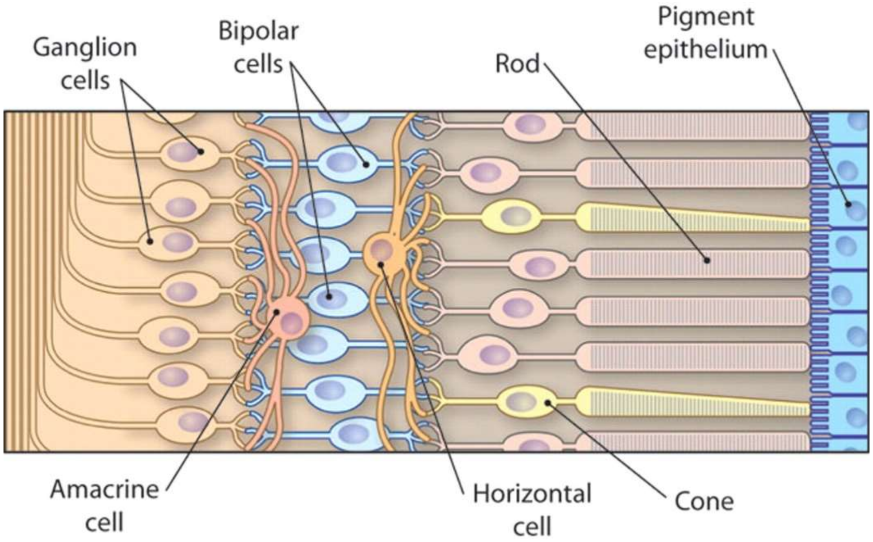


Figure 11. Retinal cells layers in human eye [51].

Lateral geniculate nucleus

The Lateral Geniculate Nucleus (LGN) is a small, almond-shaped structure located within the thalamus of the brain. It plays a crucial role in the visual processing pathway, specifically in relaying visual information from the retina to the primary visual cortex. The LGN segregates visual information into different channels or pathways. It has multiple layers, and each layer processes specific aspects of the visual scene, such as colour, contrast, and motion. The information is organized in a way that allows different types of visual data to be transmitted separately to the cortex. O'Connor., et al. showed that LGN is not only a gateway to the visual cortex but also contribute in some attentional processing. They indicated that attention influenced neural activity in the human LGN through various mechanisms: it boosted neural responses to attended stimuli, attenuates responses to ignored stimuli, and increases baseline activity when there was no visual stimulation [52]. In figure 12 the location and the structure of LGN was shown.

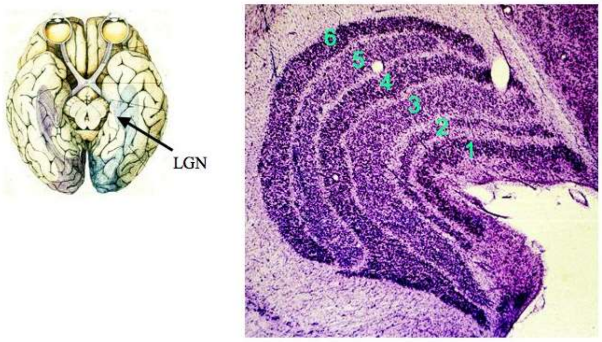


Figure 12. The lateral geniculate nucleus position and structure [53].

Primary visual cortex

The primary visual cortex, usually known as V1 area or the striate cortex is a critical part of the human brain responsible for processing visual information. It is located at the back of the brain in the occipital lobe, and its primary function is to receive and analyse visual signals. Neurons in the primary visual cortex are sensitive to specific features and orientations. The processed information is then integrated and sent to other visual areas in the brain for instance, dorsal and ventral areas, allowing us to perceive events that happens around us. Figure 13 shows the location of the primary visual cortex in the human brain.

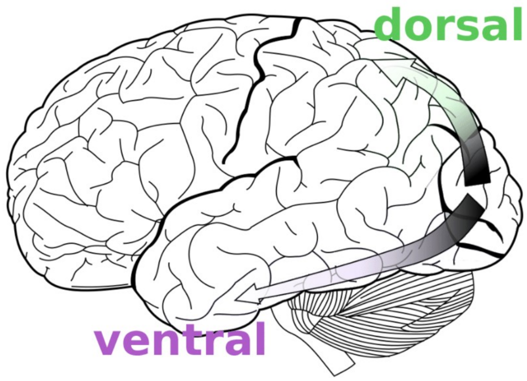


Figure 13. Primary visual cortex and dorsal and ventral pathways [54].

2.3.1 Depth perception and stereopsis

Depth perception is the ability to perceive objects in a three-dimensional space, which involves recognizing their length, width, and depth while also measuring their distance from the observer. While it is commonly believed that binocular vision is the primary foundation for depth perception, it's noteworthy that even if one eye is covered, a significant sense of depth remains. Although the perception of depth can occur with just one eye, it is typically heightened when both eyes are used together, as discussed in Schwartz's 2017 research [3]. Importantly, depth perception is not solely concerned with determining the spatial location of objects and their proximity, but also with the perception of their three-dimensional, solid shapes.

Stereopsis (from the Greek στερεο- stereo- meaning "solid", and ὄψις opsis, "appearance, sight") is a term that is most often used to point to the perception of depth and 3D structure obtained on the basis of visual information gained from two eyes by individuals with normal binocular vision [55]. Because the eyes of humans, and many animals, are located at different lateral positions on the head, binocular vision results in two slightly different images projected to the retinas of the eyes. The differences are mainly in the relative horizontal position of objects in the two images. These positional differences are referred to as horizontal disparities or, more generally, binocular disparities. The depth perception works mainly based on two types of disparity: Crossed and Uncrossed disparities. It means the direction of displacement of the retinal images. Figure 14 illustrates the focusing point and projection of crossed and uncrossed disparity on the retina well.

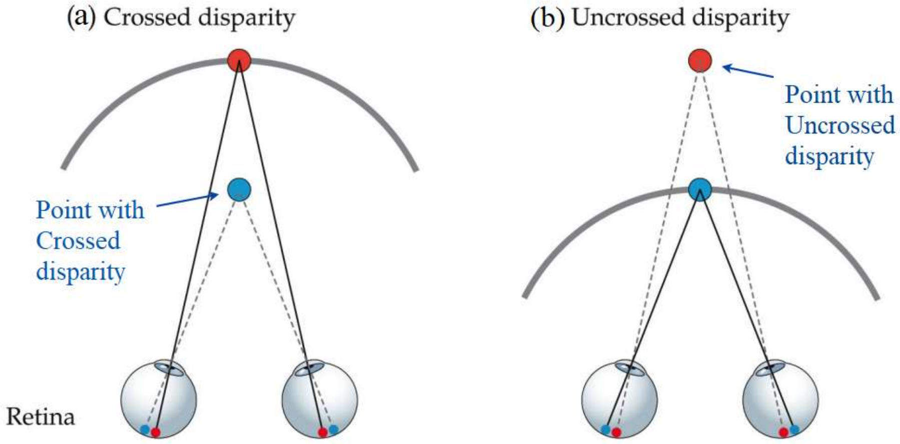


Figure 14. Retinal projection of crossed and uncrossed disparity.

Disparities are processed in the visual cortex V1 of the brain to yield depth perception [56]. While binocular disparities are naturally present when viewing a real 3D scene with two eyes, they can also be simulated by artificially presenting two different images separately to each eye using a method called stereoscopy. The perception of depth in such cases is also referred to as "stereoscopic depth" [55]. One of the most important factors to perceive the depth is illumination. Based on previous studies, the effect of equiluminat situation on stereopsis classified into four categories. 1) Significant decrease in stereopsis in equiluminance. 2) Colour still has a role but not as the same as in luminance. 3) Colour can disambiguate the ambiguous stereo in equiluminance. 4) Colour has a strong role in stereopsis [57]. To know how it is possible to measure human stereopsis ability, I need to explain two types of stereopsis: Local stereopsis, Global stereopsis. The local, or contour, stereopsis involves matching similar features or contours on the two monocular images over a smaller area of the retina. The relative locations of these monocular features are used to determine the disparity between the two monocular views without referencing other parts of the retinal field. The stereoscopic visual test Titmus fly test is designed base on the local stereopsis.[58][59]. The global stereopsis is known by Random Dot Stereogram (RDS) test. The absence of contours means that no form perception can occur until the horizontal retinal disparities have been correlated across a substantial area and the stereoscopic percept can only appear when there is binocular fusion. This process is called global stereopsis [58].

Depth cues

Depth cues are pieces of information that assist the human brain in perceiving the third dimension within visual stimuli. Since retinal images are confined to a two-dimensional surface, our visual system must reconstruct depth and distance by utilizing a variety of depth cues and making assumptions about the structure of the scene. To achieve this, our visual system relies on a combination of cues found in the retinal images themselves, as well as external signals such as oculomotor information regarding the position of the eyes. Visual depth cues can be broadly categorized into two main groups: physiological and psychological cues [60]. Physiological depth cues encompass factors like accommodation (defocus), convergence, binocular parallax, and monocular movement parallax. Psychological depth cues, on the other hand, include concepts like relative size, linear perspective, overlapping, shadowing, and shading [60][61].

Visual search and neural oscillation

Stereopsis or 3D perception has been broadly investigated in many studies. Among them, objective methods also utilized to study different aspects of 3D perception. As visual search in the three-dimensional environment depends on depth judgments [62][63], the availability of depth cues is an important aspect of images [64].

Understood from the previous section, depth cues are sources of information the weight of which changes depending on the viewing condition. At close viewing distances, the relative binocular disparity is considered to be a prerequisite for accurate depth perception [55]. It may contribute to image saliency and deployment of attentional resources across depth planes [62][63][65]. According to classical visual search models [66], there are early (pre-attentive) processes and late processes with the active involvement of attention. It has been shown both in neurophysiological and behavioural studies that the information about binocular disparity is available early in visual processing, and it manifests in later, higher-order representations. Namely, considerable differences in the amplitudes of ERPs in parietal and occipital regions were revealed already at 90-130 ms after the onset of visual stimulus when comparing brain activity during the viewing of stereoscopic and two-dimensional images [67][68][69][70][71] indicating the critical role of these brain areas in the processing of information about depth. Some studies reported slightly earlier [72] and later manifestations [73][74] of brain reactions on binocular disparity. In addition, differences in the later cognitive processes were highlighted in [63][74][75] showing that amplitudes correlated with the absolute values of binocular disparities [76] and orienting of attention [77] at 150-200 ms. In later times, the stereoscopic input modulated high-level perceptual processes involved in the integration of information [76][77][78], figure-ground segmentation [63][74][75] view generalization [72], recognition [71], and stimulus classification [74]. These processes were primarily associated with neural activity in parietal regions rather than in occipital regions.

Recent studies investigated the effect of stimuli brightness on brain activities. Results have showed different level of brightness can affect either frequency bands or ERPs, both amplitude and latency as well as electrode locations [79]. Higher luminance and brightness of the stimuli result in higher peak of posterior N95, occipital P1, and parietal and occipital N1 as well as shorter latency [80]. However, on the other hand, [81] stated that the higher brightness of stimuli result in a significant decrease in power of peristimulus alpha activity, moreover only the latency of N1 component was significantly larger in brighter condition.

Most of the research aiming at elucidating the neural correlates of processing binocular disparity was performed using stereoscopic images ranging from anaglyph-based [72][74] [78] to polarization-based separation of visual inputs [71][82]. Stereoscopy creates the illusion of image depth by separating visual inputs for both eyes, thus possibly causing binocular vision stress due to the cumulative effect of asymmetries that can induce discomfort and visual fatigue [33][82][83][84][85]. EEG assessment of user experience and performance is crucial in the field of human-computer interaction as it allows to predict the acceptance of new visualization systems and improve ergonomics [84][86][87]. In comparison to the behavioural measures, the neurophysiological ones are less biased [82]. Moreover, the reliable results can be obtained within short experimental procedures allowing to evaluate mental efforts [88].

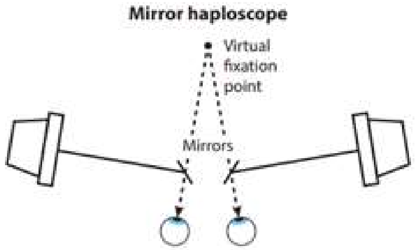
To improve user comfort and performance, new visualization approaches are being developed. To avoid the forceful separation of views for both eyes, new displays aim to provide three-dimensional images on multiple focal planes the viewing of which requires no eyewear [61][83][89][90]. Specifically, it can be ensured by presenting image points in the physical space of optical element in a time-multiplexed manner [61][90][91].

Depth perception plays an important role in visual search when it comes to finding objects in space or information in spatial images. It is crucial both in our daily lives and in the performance of professional tasks that involve qualitative or quantitative judgments about the third dimension of images. As new three-dimensional visualization systems are intended to be used daily, it is important to understand how their implementation affects user performance. Previous behavioural studies provided some experimental support for the use of volumetric visualization instead of stereoscopic images by reporting more accurate judgments on spatial relationships [92], and faster information recognition time [89]. However, to the best of our knowledge, no studies have yet assessed how neural activity changes in response to new three-dimensional visualization methods.

2.4 Three-dimensional (3D) technologies

Typically, 3D display design employs depth cues to generate three-dimensional images, though not all displays utilize these cues. Such displays can be broadly categorized into two major types: Stereoscopic 3D displays and Autostereoscopic 3D displays [60][61]. Stereoscopic 3D displays primarily rely on simulating binocular parallax depth cues, generating separate images for each eye. As a result, viewers must wear special glasses to perceive two slightly displaced images. Stereoscopic displays include Colour-Interlaced (Anaglyph), Polarization-Interlaced Display (Passive Display), Time-Multiplexed Stereoscopic Display (Active Display), and Head-Mount Display. If looking deep into stereoscopic displays, they can be divided into two general types: nonoverlapping optical path and overlapping optical path to the two eyes. Nonoverlapping solutions employ either two distinct displays or two separate areas on a single display to deliver unique images to each eye. Examples include head-mounted displays, near-eye displays, and mirror haploscopes. Figure 15 (a) shows the structure of nonoverlapping method. Virtual-reality and augmented-reality use this technique because in nonoverlapping method two displays must be too close to the eyes to provide a wide field of view and the distance between the displays and eyes should be fixed. The overlapping solution is much more common and uses coding method to separate the image for each eye. This technique can be seen in anaglyph, polarized, and temporarily alternating displays. Figure 15 (b) well describes the overlapping technique [93].

(a) Nonoverlapping stereoscopic display



(b) Overlapping stereoscopic displays

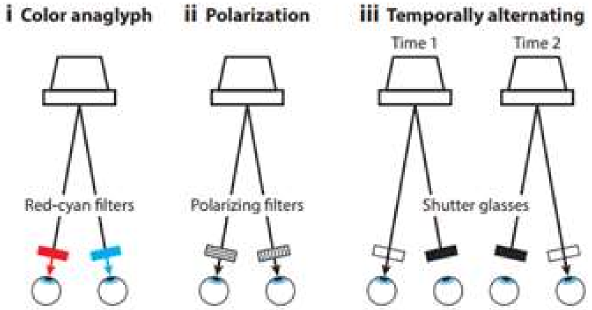


Figure 15. Techniques for image separation in stereoscopic displays. (a) Nonoverlapping display (mirror haploscope). (b) Overlapping displays [93].

Anaglyph displays function by encoding different wavelengths of light for each eye, creating a stereoscopic effect. This is achieved by presenting the image in two distinct colours, typically red and cyan. To view the image in 3D, a viewer wears special glasses equipped with two filters, one for each eye, corresponding to the colours used in the image. The distance between the red and cyan images in the display is known as disparity, and the greater this distance, the more pronounced the depth effect.

There are two types of disparity: uncrossed and crossed. Uncrossed disparity occurs when the position of each coloured image in the display coincides with the filters on the glasses. In other words, the red image is seen through the red filter and the cyan image through the cyan filter. This creates a natural and comfortable viewing experience.

On the other hand, crossed disparity occurs when the position of the red-cyan colours in the image is opposite to the position of the red-cyan filters on the glasses. This means that the red image is seen through the cyan filter and the cyan image through the red filter. This can lead to a more exaggerated 3D effect but may also cause discomfort or eye strain for some viewers. [94]. Figure 16 shows the crossed and uncrossed disparity in anaglyph method.

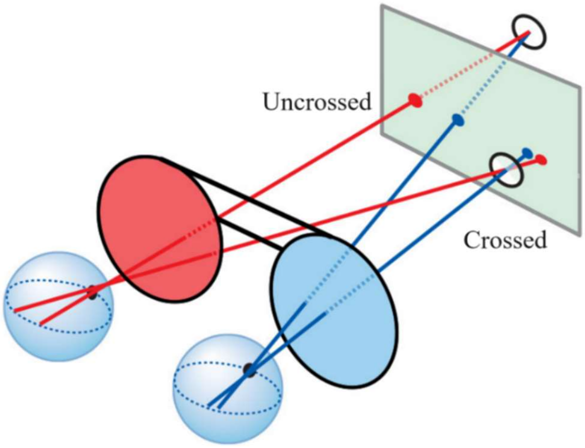


Figure 16. Crossed vs Uncrossed disparity and the depth effect in an anaglyph image [95].

An alternative method to encode the left and right imagery involves polarization. The light emitted by the display is polarized in orthogonal directions for the left and right eyes. The viewer then wears analysers, which direct one polarization to one eye and the orthogonal polarization to the other eye (see figure 15 (b)) [93].

In contrast, Autostereoscopic 3D displays simulate all depth cues, allowing viewers to obtain additional information about the observed object by changing their position. This category further divides into three subtypes: multi-view display, volumetric display, and digital hologram display [90]. Since the volumetric multiplanar display employed for this study, the focus is on the structure and function of the volumetric display.

Volumetric Multiplanar Display

As noted earlier, there has been a growing emphasis on advancing stereoscopic displays in recent years. However, these displays fall short of generating authentic 3D images and consequently possess certain limitations. Specifically, they rely solely on binocular disparity (static parallax) as a depth cue to create 3D images, neglecting other depth cues [90]. Notably, there exists a category of displays known as volumetric multiplanar display, defined as "a transparent physical volume (image space) in which static and animated image components may be placed." These displays inherently provide a dynamic stimulus to accommodation due to the presentation of image points at various locations within a physical volume, thereby presenting 3D effects with congruent cues to vergence and accommodation, mitigating conflicts.

Multiplanar 3D displays operate by constructing 3D images, leveraging the persistence of vision to integrate multiple 2D pattern-carrying surfaces into a 3D volume [96]. 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. Autostereoscopic 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.

One of the technical challenges in the visualization system lies in the generation of multi-planar volumetric image slices. 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 [97], as illustrated in the accompanying figure 17.

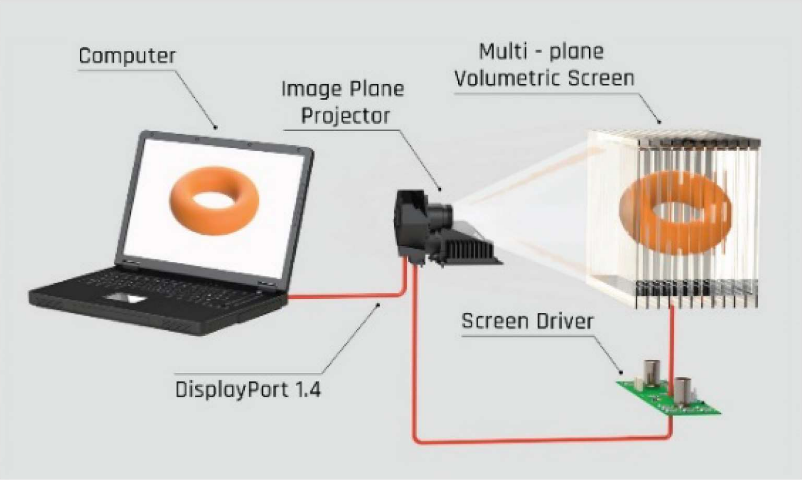


Figure 17. Structure of a volumetric multiplanar display [97].

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. Since the main concept of the thesis is application of EEG in depth perception evaluation, the comparison of brain dynamics in different condition of visualization systems could have a scientific value to show the effectiveness of the brain signal analysis method in detecting the depth perception while looking on different display systems. Therefore, the first study, as a bachelor's final thesis, conducted based on the comparison of brain activities between two visualization systems known as anaglyph and volumetric multiplanar displays. In general, for the objective assessment, ERP analysis and continuous frequency bands were under inspection.

The second study, as another bachelor's final thesis, conducted based on the concept of the potential of brain signal analysis in detecting any differences between crossed and uncrossed disparity presented on a flat panel display in form of anaglyph visualization because binocular disparity is a strong cue in depth perception.

Third study designed based on the concept of perceiving 3D and 2D on one type of display and since the volumetric display is at the centre of attention in this thesis, evaluation of the brain activities in form of ERP and frequency bands was performed to research the depth perception on the volumetric display.

At the end, the potential of EEG data analysis in detecting any differences in brains activity in external environmental conditions were under investigations. Two different lighting conditions known as photopic and scotopic designed to study the 3D image perception on the volumetric display by EEG data analysis. Since light reflections and its effect on the contrast of visual targets can affect the depth perception, therefore, research the illumination effect on the volumetric image 3D perception was the main concept of the study.

The main principle of the recording data in all studies was almost the same; however, there were some differences in concept and data analysis. In the following sections, the main principle of each study-design has been explained in detail.

3.1 Participants

Participants were chosen of any ethnicity. Eighty-eight subjects participated in the study, comprising 30 males and 58 females, with an average age of 25±4 years. They voluntarily joined the research, and before commencing the experiment, an informed consent paper (see appendix 1) signed. In addition, optometric visual tests were conducted to ensure their normal binocular vision function. Inclusion criteria for participants were established, including normal or corrected-to-normal visual acuity (1.0 or better, decimal units), absence of binocular dysfunctions and colour deficiency (controlled by Ishihara test), and a stereoscopic acuity of 40 arcsec or better (measured using a Titmus stereo test, Stereo Optical Co., Chicago, IL). Thus, the participants were chosen from normal group of people to ensure they have a good vision and stereo acuity.

Seven participants were excluded from the study: Three of them did not meet the optometric criteria, two of them exhibited noisy brain signals likely due to electrode failure, and the rest displayed a high rate of mistakes in task performance. Consequently, the final participant count was 81, comprising 27 males and 54 females, with an average age of 25±5 years. Importantly, all participants were unaware of the specific purpose of the study.

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). This display incorporates twenty physical image depth planes and utilizes short liquid-crystal-based light diffuser elements that function as temporary image receiving screens. These diffusers are synchronized with a high refresh-rate image projection unit [90]. During operation, the diffusers rapidly switch between a highly transparent state and a light-diffusing state, ensuring an overall volumetric image refresh rate of 60 Hz. The resolution of the display was 1024 × 768 pixels per image depth plane. (See figure 18)

Figure 18. 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. Passive stereo goggle with red-cyan filters were employed to complete the producing of a stereoscopic image.

3.3 Procedure and Task

The general structure of the procedure and task was the same in all experiments with a little difference. First, the procedure and the aims of the task were explained to the participants. Then, the participants provided written informed consent (Appendix 1). Participants' visual acuity and stereoscopic acuity were screened. All studies were done in scotopic or dark room condition with an illuminance of 1.2 lux. The study of "effecting the lighting condition on volumetric 3D depth perception" was conducted in two different lighting condition. The first condition was scotopic condition, with an illuminance of 1.2 lux. The second condition was a lit room, known as the photopic condition, with an illuminance of 1146 lux.

The visual stimuli illuminance and contrast was measured by KINICA MINOLTA CHOROMA METER CS-100A. In the scotopic condition, the volumetric visual stimuli had a contrast (calculated by weber formula) equal to 7.04. The target luminance was 1.93 cd/m^2 and the background was 0.24 cd/m^2. The anaglyph visual stimuli had a contrast equal to 7.2 which the target luminance was 1.64 cd/m^2 and the background was 0.2. cd/m^2. In the photopic condition, the volumetric visual stimuli had a contrast equal to 3.92. The target luminance was 18.2 cd/m^2 and the background was 3.7 cd/m^2.

Each experiment included a total of 160 trials. The 3D demonstration occurred in 50% of the trials in a pseudo-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 (a target) had a different binocular disparity in comparison to three others (distractors), because of which it appeared closer to the viewer, shown in figures 19 (a) and (b). Participants had to search for a target and report its relative location within the display by choosing one of four responses (up, right, down, and left). For the response, the arrow keys of a computer keyboard were used. After the response submission, the fixation cross reappeared, and the subsequent trial followed. The entire time of the task performance was on average 10 minutes depending on the response time. All target positions were counterbalanced across directions. In the 2D trials, all rings were presented at one depth plane; thus, the search elements contained equal disparity. The subjects responded to the 2D trials by pressing the space button on the keyboard. Thus, participants had to press one of five choices for responding, four directional keys and Space key on the keyboard. The experiment was not time constrained. However, the participants were instructed to complete the task as accurately and quickly as possible. Participants sat facing the display at a viewing distance of 90 cm (see figure 19(b)).

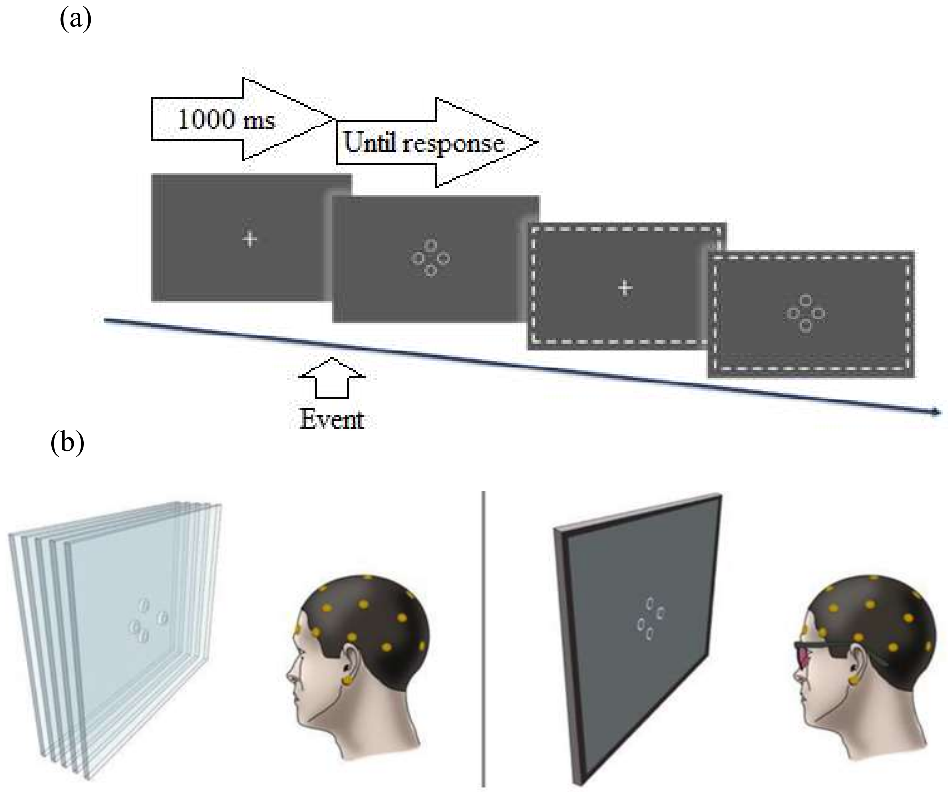


Figure 19. (a) The experiment design paradigm contained 160 trials of ring presentation that half trials had zero binocular disparity. (b) Schematic illustration of the setup and stimulus on the volumetric multi-plane display and flat panel display.

In crossed and uncrossed disparity experiment, the visual target had the same dimensions as the volumetric visual target. In addition, the room illuminance was the same as 1.2 lux. The red-cyan (red filter over the right eye) goggle was worn by participants. Figure 20 shows the visual target in form of anaglyph for crossed and uncrossed disparity.

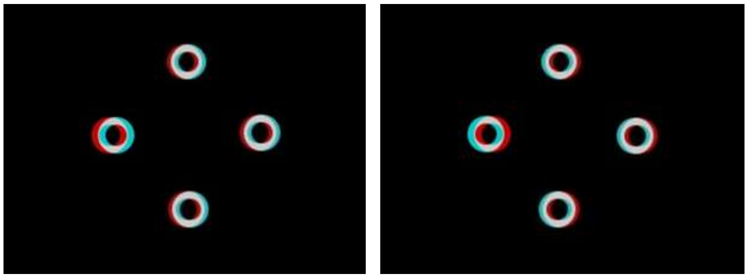


Figure 20. The visual target for the crossed (left) and uncrossed (right) disparity (red filter was in front of the right eye).

3.4 EEG data recording and analysing

The most sensitive part of the study was recording the raw data of the brain activity. The Nicolet v32 EEG system was employed to record the electrical activity of the brain. 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 22). The reference and ground electrodes attached to top the scalp. Data collection occurred at a sampling rate of 1024 Hz, with a band-pass filter applied from 0.5 to 70 Hz. The electrode montage was based on Vanderbilt organization. The impedance between electrodes and scalp skin was kept below 10 KΩ to eliminate the effect of noise and increase the signal to noise ratio, and EEG signals were continuously recorded during the visual search tasks. Simultaneously, task performance was recorded in a video file by a high-speed camera with a low recording latency (100ms) to use as a reference for placing markers (events for ERP analysis).

The open-source toolbox EEGLAB 2022.1.0 connected to MATLAB R2020a (MathWorks Inc., Natick, MA, USA) was used for EEG data analysis. Each event (appearance of the visual target) marked manually after the continuous recording. Then the recorded file transferred to MATLAB R2020a for further data processing. (Figure 21)

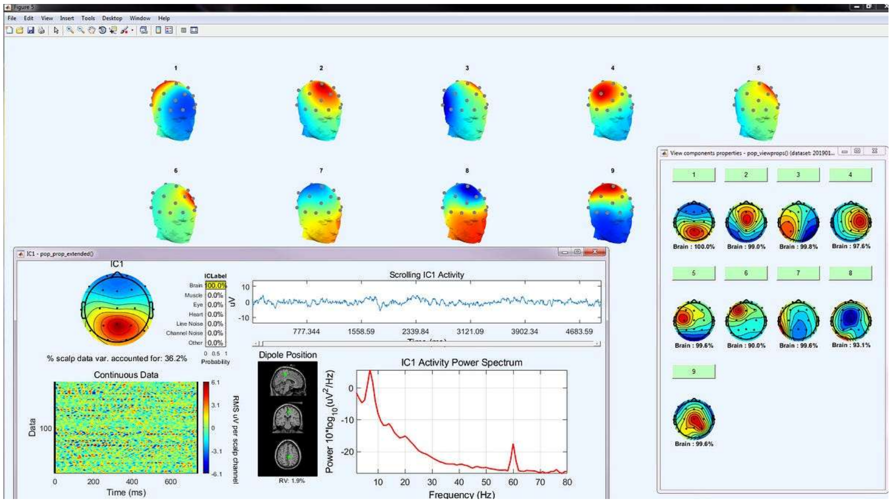


Figure 21. Schematic of EEGLAB 2022.1.0

The first step in data analysis is adding channel location to define the position of each electrode for the software. Then changing the sampling rate to the level of 256 from 1024 Hz to decrease the load of data processing. After that, EEG recordings were purified to reject any artifacts using a two-step procedure that involved the built-in software algorithm and visual inspection of variance to reject noise, including baseline, blinking, and muscle activity. Then Independent Component Analysis (ICA) was run to analyse the power spectral density. Finally, signals were separated into time-locked epochs of 1200 ms duration synchronized with the onset of search arrays, containing 200 ms of prestimulus. Only correct responses were analysed, and trials with false alarms or misses were excluded. ERP components' peak amplitude and latency were determined by visually inspecting the waveform within the time-window of -200 ms to 1000 ms.

Figure 22. The experiment set up and electrodes placement.

3.5 Statistical analysis

Different study designs needed different statistical analysis. The differences in mean amplitudes of ERPs were evaluated using a three-way analysis of variance (ANOVA) based on repeated-measures factors: stimulus condition (three-dimensional image and two-dimensional image), visualization system (flat panel display and multiplane display), and electrode (O1, O2, P3, Pz, and P4). The F statistic degrees of freedom were adjusted by Greenhouse-Geisser correction where the assumption of variance sphericity was violated according to Mauchly's test. The size of statistically significant effects was estimated by generalized eta squared (η^2G) indices. The R software package was used for ANOVA analysis. Pairwise correlated samples t-tests were used for the post hoc comparisons. To control the family-wise error rate, pairwise comparison p-values were adjusted by the Bonferroni correction.

4. Results

Since the concept of the thesis was application of EEG for volumetric 3D image perception, the results divided into separate parts based on each experiment which was designed to be clear and understandable.

4.1 Brain activity when viewing anaglyph vs volumetric 3D

4.1.1 Performance Data

The behavioural results showed that most targets were found correctly for both types of visualization, which was reflected in the high mean correct response rates, and the low variability of data. Across all participants, 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. However, more errors were made when individuals responded to target-absent stimuli on both displays. Specifically, 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. A 2 (visualization system: multi-plane display, volumetric display) × 2 (stimulus condition: target-present, target-absent) 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 ($F(1, 19) = 0.005$, $p = 0.95$, $\eta^2_G < 0.001$) and interaction ($F(1, 19) = 0.07$, $p = 0.79$, $\eta^2_G < 0.001$) were not significant.

In addition to the correct response rates, response times (RT) were analysed for the evaluation of visual search outcome. The mean time was considerably shorter when the visual search arrays were presented on the multi-plane display than on the flat-panel display (see figure 23). The statistical analysis revealed that there were significant main effects 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 ($F(1, 19) = 0.12$, $p = 0.73$, $\eta^2_G < 0.001$).

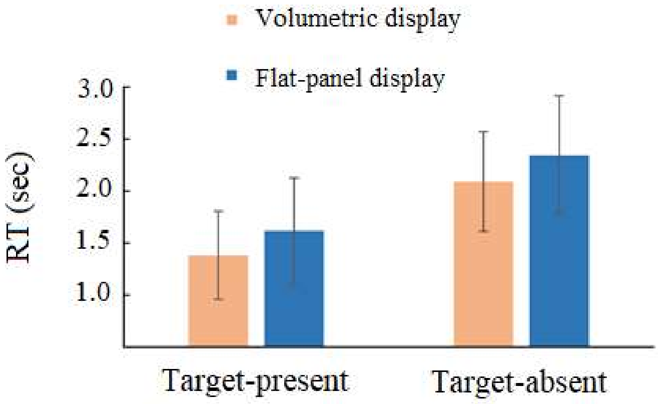


Figure 23. Averaged response times when the feature visual search arrays were presented on the multi-plane display and flat-panel display. Error bars depict standard deviations.

4.1.2 Electrophysiological Data

The continuous EEG signals was recorded when the subjects performed the visual search tasks. As expected, brain activity was high in occipital and parietal regions. Figure 24 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.

To differentiate the effect of the third dimension of images generated in different ways from other aspects, the amplitudes of ERPs were also included when participants were viewing target-absent images (with all elements containing the same disparity) on both displays in the data analysis.

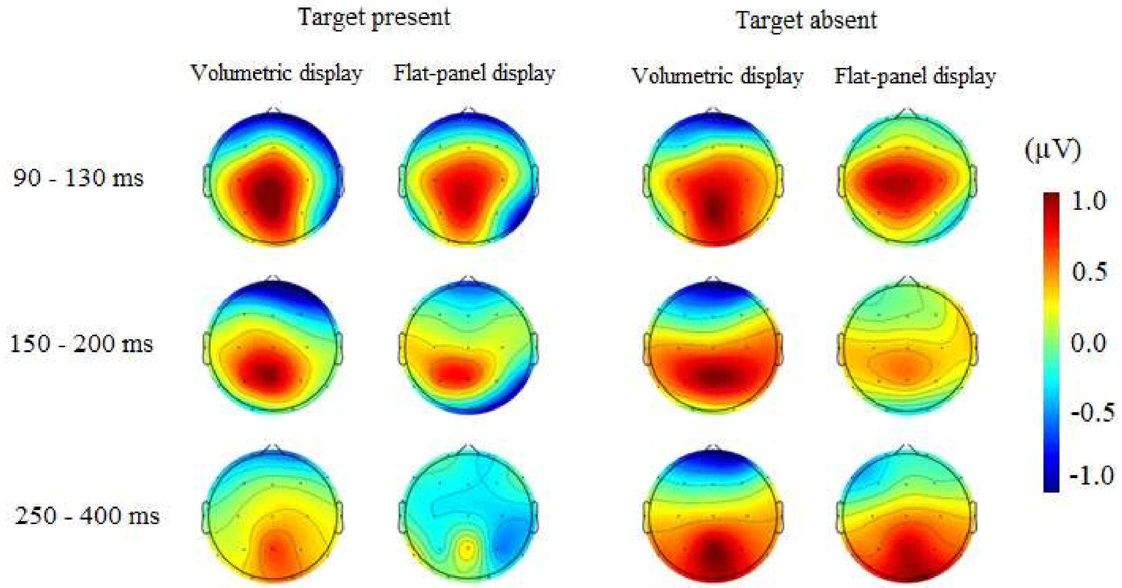


Figure 24. ERP topographical maps reflecting the brain activity during three time-windows, averaged across all participants when viewing target-present images and target-absent images on two visualization systems, i.e. multi-plane display and flat-panel display.

4.1.3 Waveforms

P1 mostly appears at the occipital lobe. As it was seen in waveform figures (figure 25), non-target volumetric P1 amplitude had the highest amount at all electrodes. N1 and P2 components follows the P1 usually appear 130 ms and 200 ms respectively after a visual stimuli [37]. The results showed the highest negative deflection was belong to non-target anaglyph at all electrode locations. Moreover, the highest positive deflection happened within time window 100-180ms reflecting P2 component. It was seen that non-target volumetric had the highest amplitude of P2 at all electrode sites. (see figure 25). Finally, P3 component is the most extensively researched ERP component that occurs in response to stimulus type approximately 300 ms after stimulus onset. In addition, the result showed that P3 of non-target, both in volumetric and anaglyph had larger amplitude and latency in respect to the target experiment on all electrodes' sites. The highest amplitude was for non-target anaglyph. Target volumetric also had a higher potential than 3D anaglyph at all electrodes.

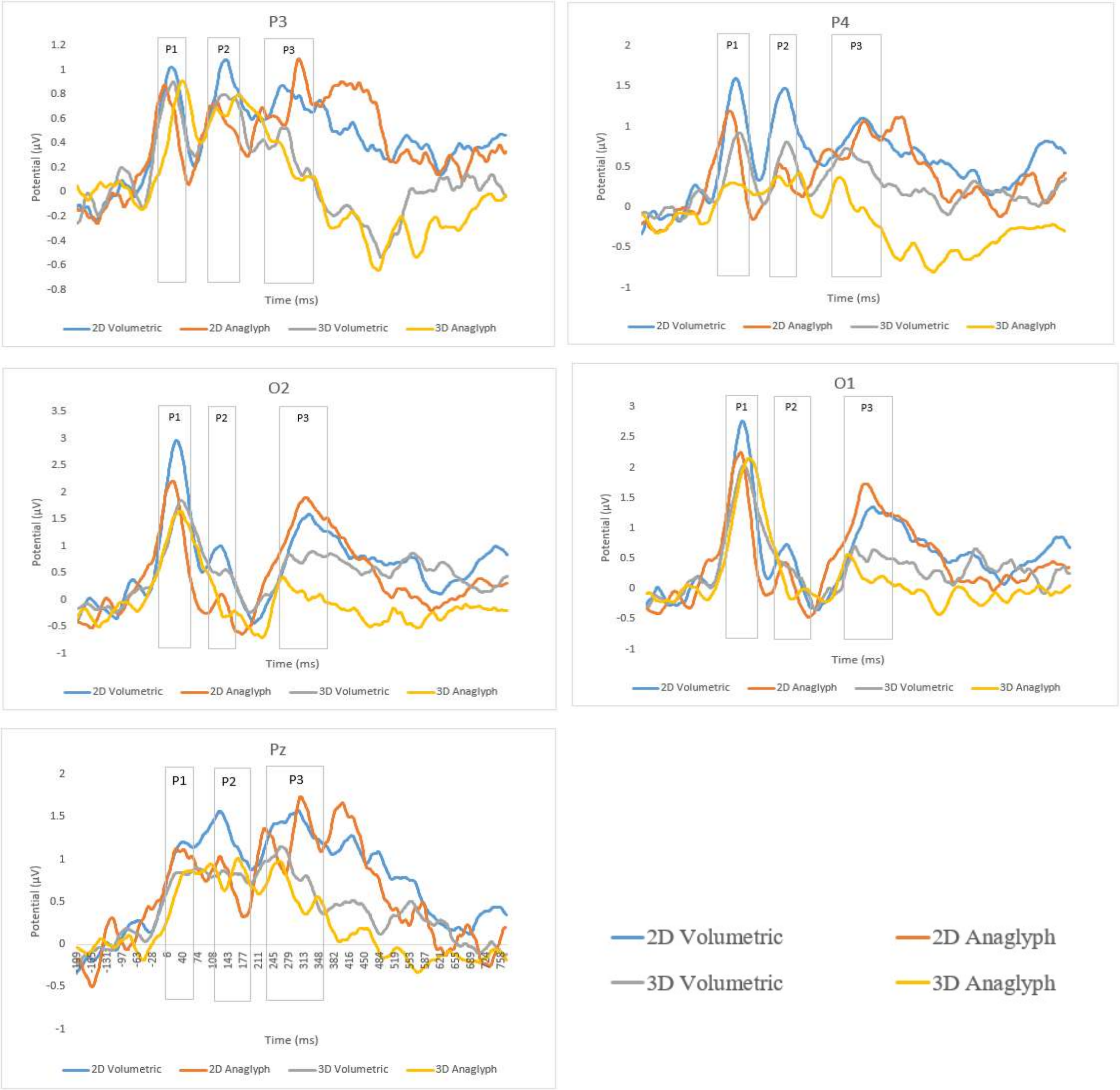


Figure 25. Waveform of five electrodes showed the main ERP components over an epoch including four conditions of target and non-target, volumetric and anaglyph visualization.

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 ($F(2.0, 38.2) = 10.4$, $p < 0.01$, $\eta^2_G = 0.060$) 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. However, it should be added that both effect sizes were small according to Cohen's scale. No significant effect of the visualization system 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 period of 150-200 ms after the onset of the visual search array, 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 electrode ($F(4, 76) = 44.2$, $p < 0.01$, $\eta^2_G = 0.243$). No significant effect of the stimulus condition 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 ($F(1, 19) = 39.5$, $p < 0.01$, $\eta^2_G = 0.265$) and electrode ($F(2.5, 48.1) = 12.7$, $p < 0.01$, $\eta^2_G = 0.076$) in the analysis of brain activity during 250-400 ms after the onset of visual search array. According to Cohen's scale, there was a large effect size of stimulus condition on ERPs. Moreover, the interaction between stimulus condition and visualization system was demonstrated as significant ($F(1,19) = 4.6$, $p = 0.05$, $\eta^2_G = 0.028$). 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 negativity in the parietal area.

In addition to ERPs, changes on frequency bands were evaluated. Figure 26 plots the average power spectrum of neural oscillations on EEG channels in the parietal lobe and occipital lobe. As seen in Figure 26, 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).

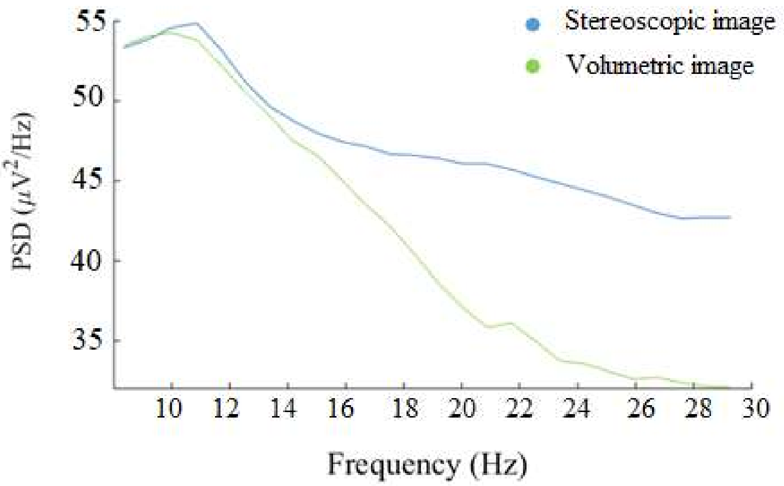


Figure 26. Average power spectrum for EEG channels in the parietal lobe and occipital lobe.

Pairwise comparisons were run using *t*-tests. Although, no considerable differences were revealed when comparing alpha oscillations on every electrode across two types of three-dimensional visualization ($p > 0.08$), beta oscillations were 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 27 plots the average power of beta oscillations on EEG channels in the parietal lobe and occipital lobe in a comparative manner for stereoscopic and volumetric images.

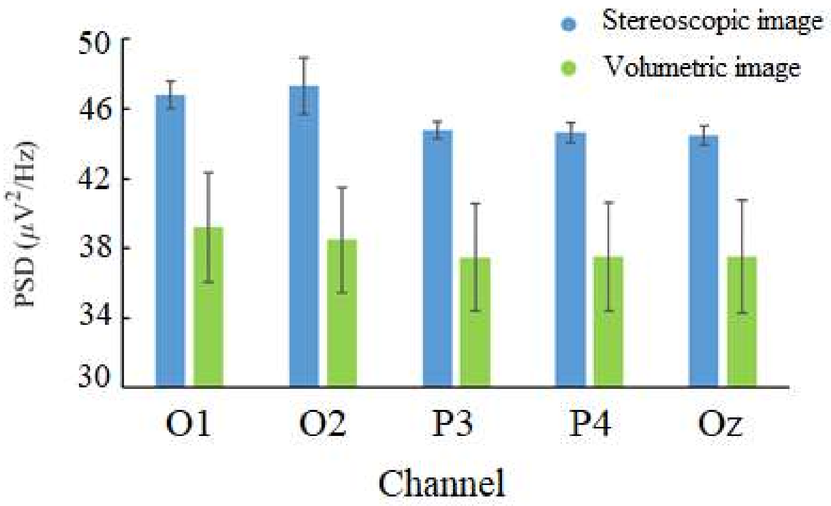


Figure 27. Beta oscillation power on EEG channels in the parietal lobe and occipital lobe. Results are averaged for all participants subjected to feature search tasks in two types of 3D displays.

4.2 Brain activity when viewing crossed and uncrossed 3D anaglyph image

Since there was only one option in disparity presentation on the volumetric display, (the visual target was closer to the subjects), another study conducted to evaluate the effect of disparity on the brain activities. 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 Performance Data

The behaviour performance data, as depicted in figure 28, 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.

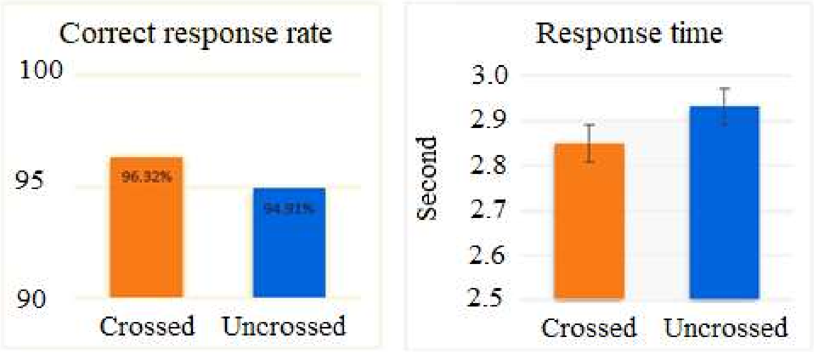


Figure 28. The average correct response rate (left) and response time (right) for crossed and uncrossed disparity present on a flat-panel display.

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 during the perception of disparity was 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.

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 29).

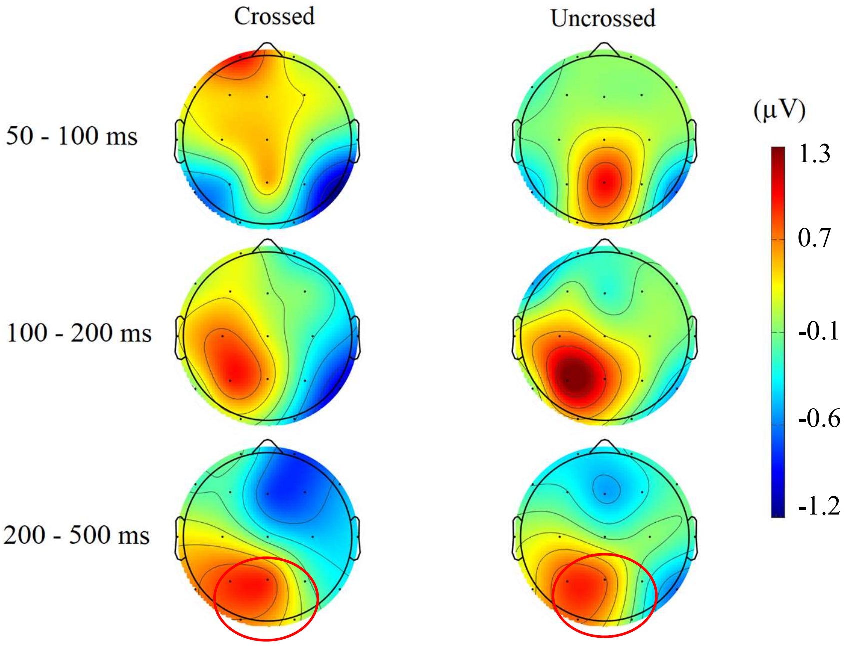


Figure 29. Topographical plots of ERP components in three time-windows for crossed and uncrossed disparities showed on a flat-panel display. Five occipital and parietal electrodes indicated in the figure.

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 30 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 ($p = 0.08$).

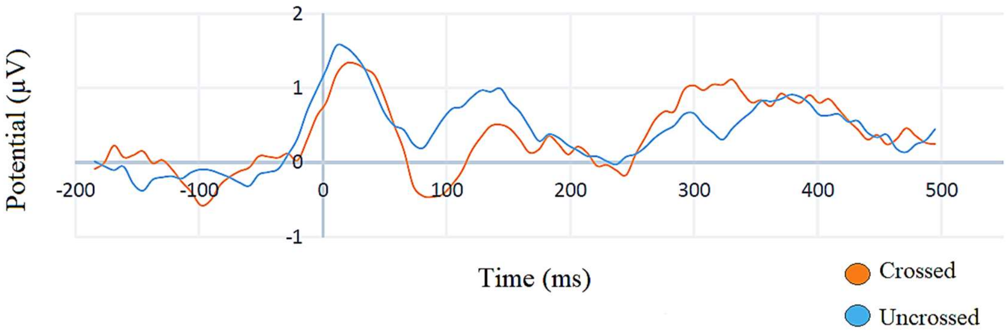
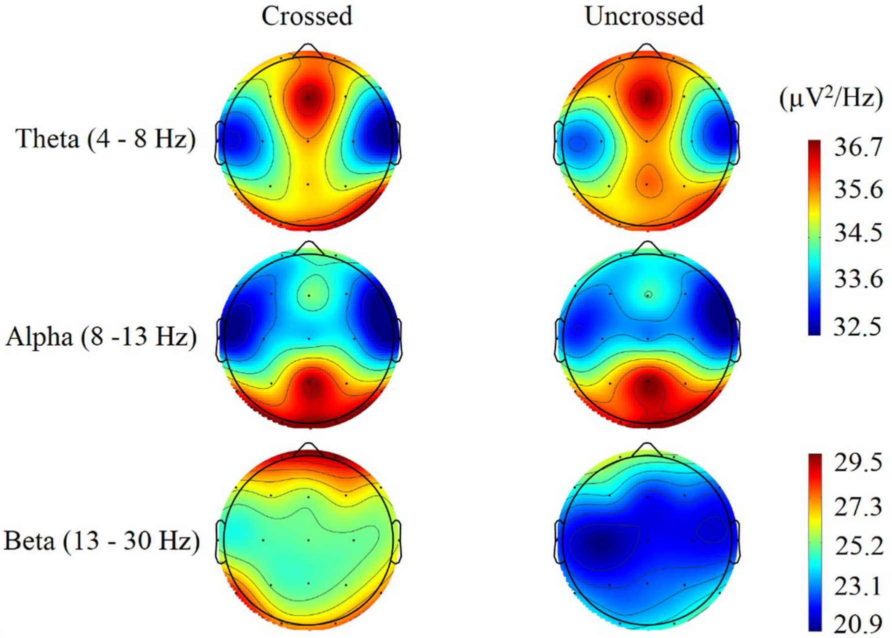


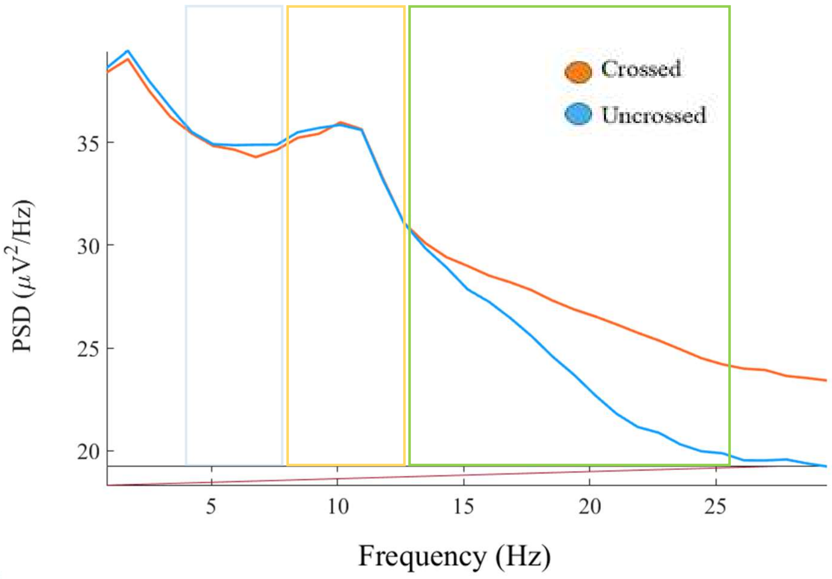
Figure 30. The waveform plots of ERP average of five electrodes (P3, P4, Pz, O1, and O2) for crossed and uncrossed disparities showed on a flat-panel display.

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 31 (a) and (b) respectively.



(a)



(b)

Figure 31. 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 when viewing 3D vs 2D image on the volumetric display

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 rate, Response Time (RT) analysed to evaluate visual search outcomes. The statistical analysis revealed in Figure 32 that there were no significant main effects of the stimulus condition.

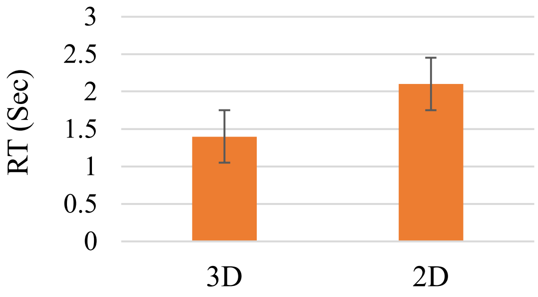


Figure 32. Averaged response times when the visual stimuli were shown as 2D and 3D. Error bars depict standard deviations.

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 33 shows changes in amplitudes of ERPs at three time-windows averaged over all participants in the form of topographical maps. Moreover, figure 34 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 significant 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.

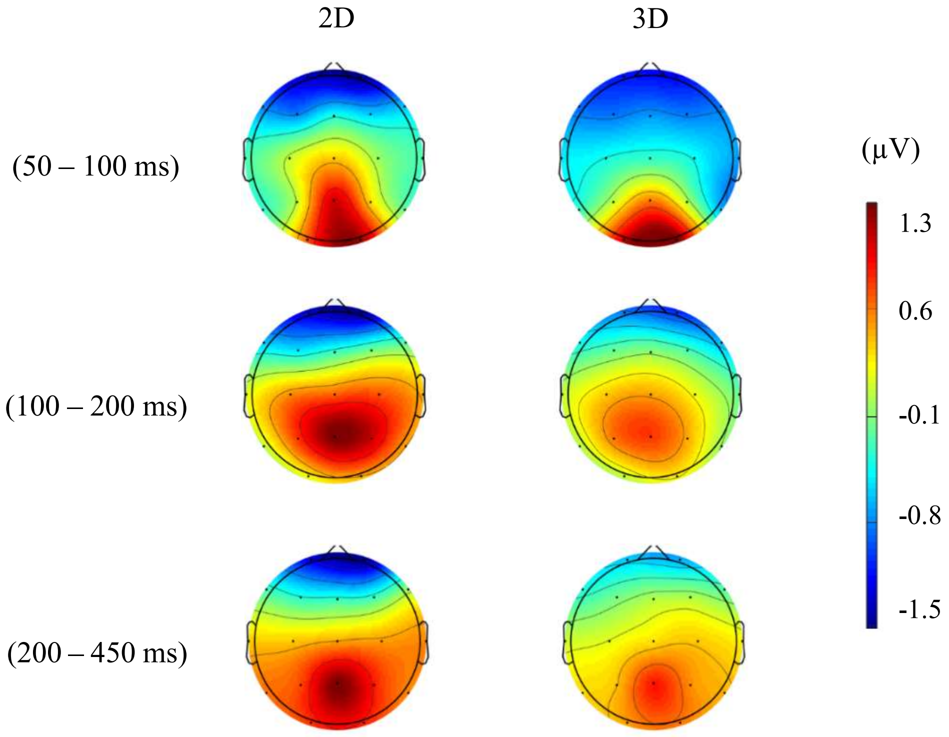
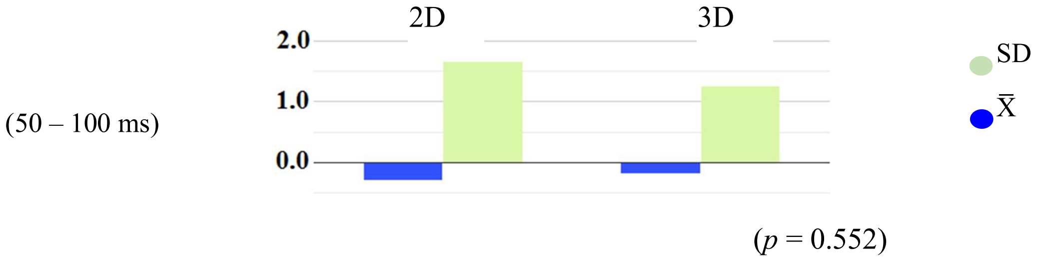


Figure 33. ERP topographical maps reflecting the brain activity during three time-windows, averaged across all participants when performing the 2D task and 3D task on volumetric multiplanar display.



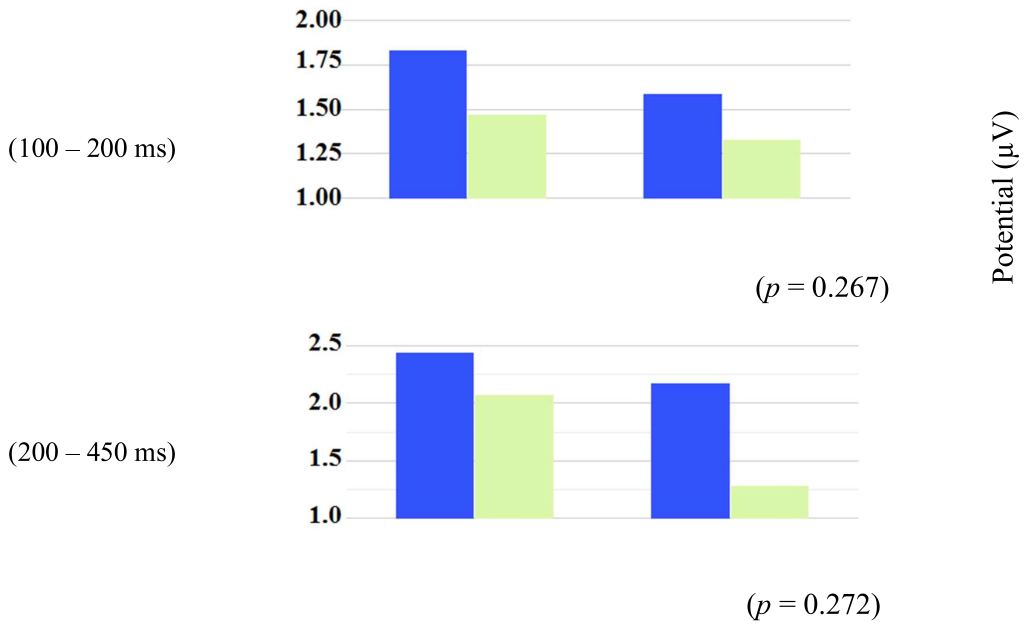


Figure 34. Average and standard deviation of five electrodes P3, P4, O1, O2, and Pz across all participants. P-value represents no statistically significant differences in each time window.

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 35 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.

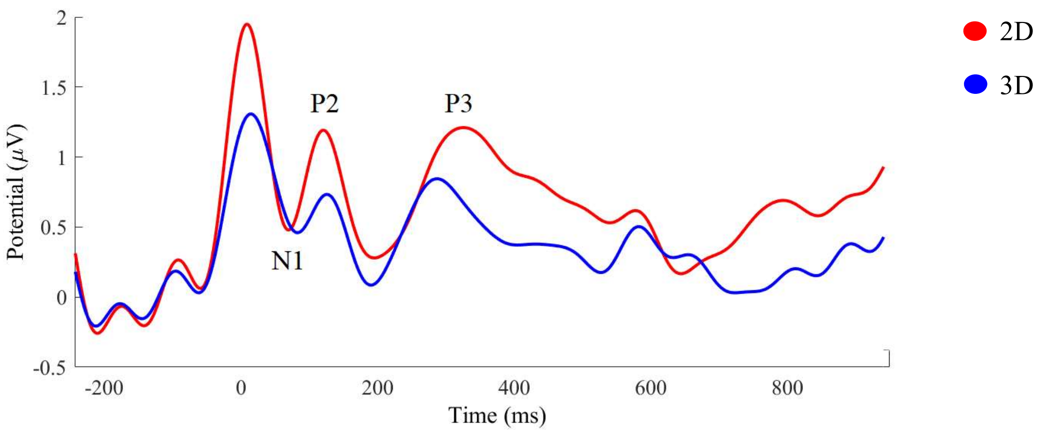


Figure 35. The waveform average of five electrodes O1, O2, P3, P4, and Pz in two conditions between -200 to 1000ms, across all subjects.

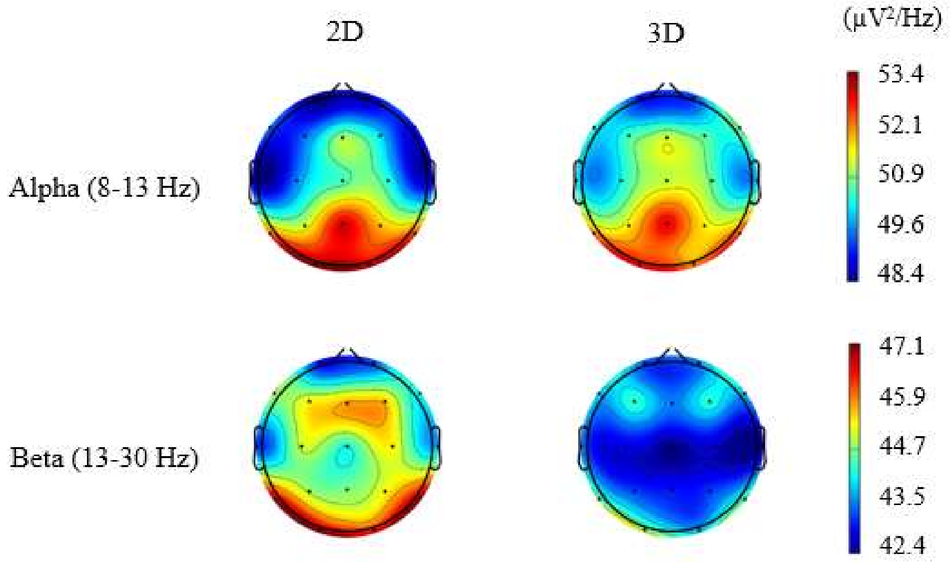
The latency analysis of ERP components showed no statistically significant differences between the two conditions except for the Pz electrode and within the time-window 200-450ms, which corresponds to the P3 component. The average latency results are summarized and reported in Table 1.

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

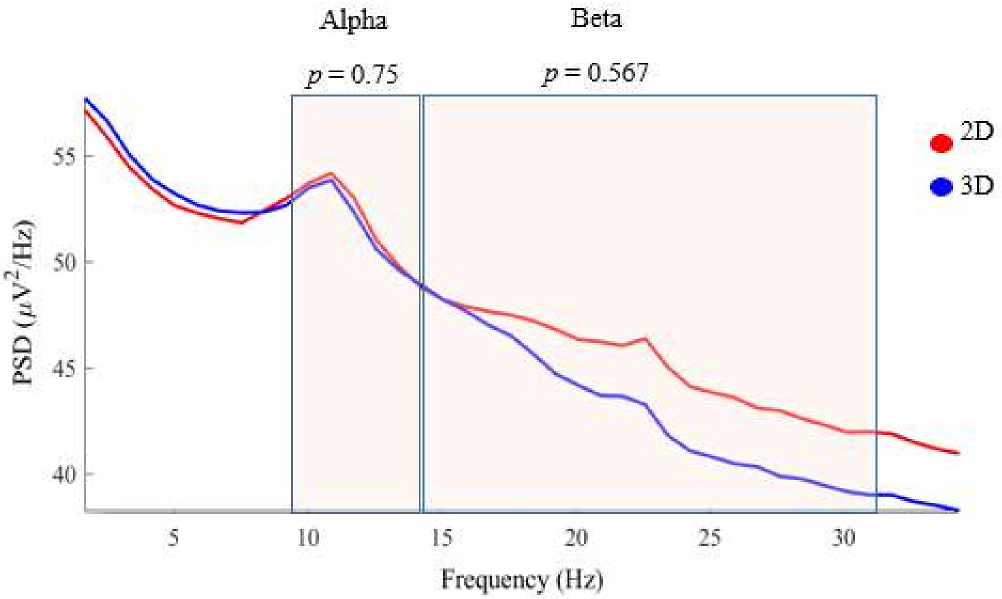
Electrodes	50-100 ms			100-200 ms			200-450 ms		
	2D	3D	*p*-value	2D	3D	*p*-value	2D	3D	*p*-value
P3	75.5±18	77±16	0.217	155.5±26	152.5±24	0.701	299±71	309±73	0.677
P4	84±13	85±12	0.796	144±22	138±22	0.421	311±84	322±74	0.711
O1	87±14	85.5±18	0.848	141±27	142±27	0.92	320±70	336±65	0.524
O2	88±11	83±17	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 frequency bands; however, the difference was not statistically significant. Topographical maps and waveforms of alpha and beta showed in figure 36 (a) and (b), respectively.



(a)



(b)

Figure 36. (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 power. Beta wave shows higher activation in the 2D condition compared to the 3D.

4. 4 The impact of different lighting conditions on volumetric 3D 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, $p = 0.9$, $\eta^2_p = 0.0006$). Moreover, there was no statistical difference between the first and last experiments (F (1, 26) = 1.264, $p = 0.27$, $\eta^2_p = 0.05$). 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 37 shows the average of each group.

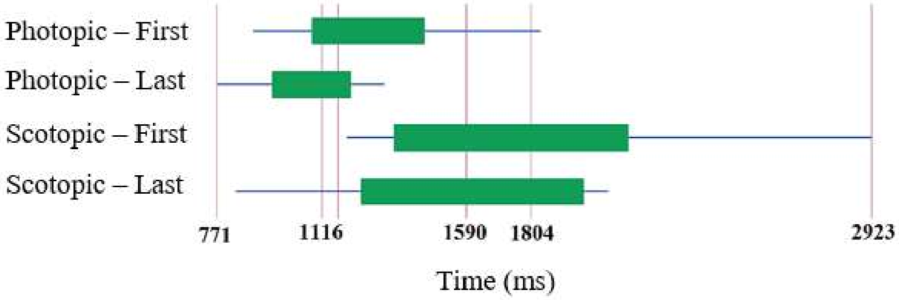


Figure 37. The average response time of each participant in each group of lighting conditions and experiment order.

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 38, 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.

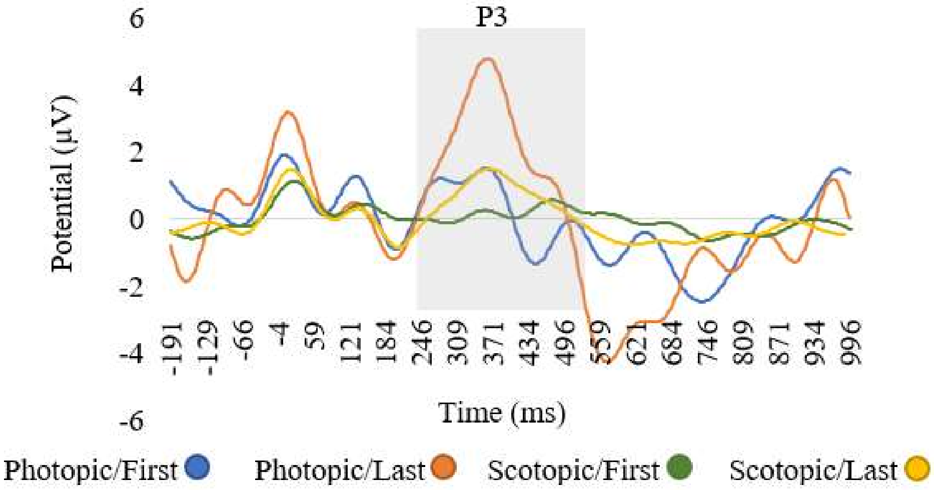


Figure 38. The average of five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) across all participants. P3 peak highlighted on the waveform.

Besides the waveform, 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 between the first and last experiments (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 39 shows the peak amplitude of each group.

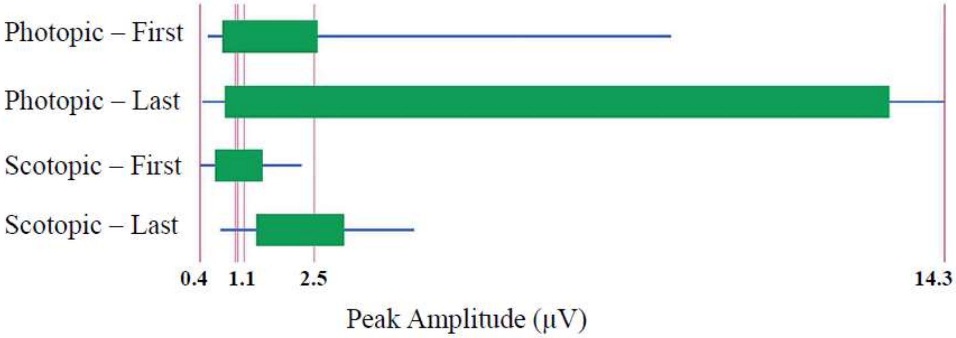


Figure 39. The peak amplitude average of five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) in different lighting conditions and experiment order.

Moreover, about the 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 (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 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 Last (M = 368.4, SD = 40.7), t(14) = 1, $p = 0.367$ experiment. Figure 40 shows the peak latency of each group.

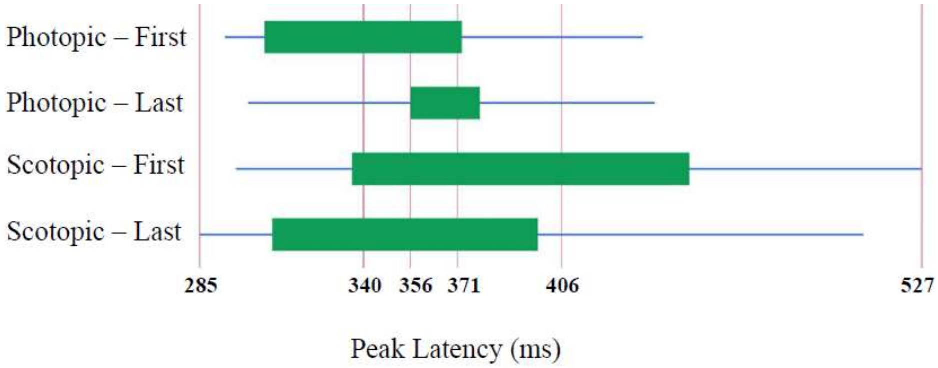


Figure 40. Peak latency average of five occipital and parietal electrodes (O1, O2, P3, P4, and Pz) in different lighting conditions and experiment order.

5. Discussion

5.1 Brain activity when viewing anaglyph vs volumetric 3D

In this exploratory study, both performance and neural activity in the context of feature visual search were evaluated, specifically focusing on the varied generation methods of the third dimension of the target. Two distinct visualizations, first, stereoscopic visualization on a flat panel display and second, volumetric visualization on a multi-planar display, were employed for comparative analysis. Consequently, our findings represent a novel revelation, highlighting substantial distinctions in late cognitive processes within the posterior regions of the brain contingent upon the specific type of three-dimensional information visualization.

When assessing the ergonomics of displays, it is crucial to understand that the user's experience and performance are depend upon the physical attributes of images, as well as the visual perception and attention [4]. Furthermore, in contrast to the prevalent use of two-dimensional visualization systems, the assessment of three-dimensional visualization requires careful consideration of the display's capacity to accurately render image depth without compromising user performance. Although alternative display technologies are available [61][89][98][91], stereoscopic displays currently dominate the market. However, stereoscopic displays are acknowledged for inducing user experience issues linked to disparities in visual inputs, leading to visual fatigue [99] and user discomfort [82][84][100].

Presenting information in a three-dimensional format has many advantageous for educational and professional purposes [101]. The depth effect of 3D image is believed to enhance attention deployment [4][62][102]. In both displays utilized, images were created with distinct binocular disparity between the target and distractors. Behavioural outcomes demonstrated that individuals accurately discerned the relative depth of items in both experiments, leading to high search performance. Consequently, our results affirm that binocular disparity serves as a strong cue, particularly at close viewing distances [55], and both displays effectively incorporate this depth feature into images.

The employment of binocular disparity as a useful cue was found to enhance user performance [65][72]. However, the stereoscopic display resulted in a longer completion time for the visual search task performance. These findings align with a previous study indicating faster response times when information was presented on multiple display layers as opposed to virtual planes [89]. Conversely, no significant differences in mean accuracy of visual search across displays were observed, likely attributable to the absence of time constraints in our experimental design, allowing individuals sufficient time and motivation to perform the task accurately. Furthermore, performance accuracy in the comparative assessment of three-dimensional visualization technologies varies depending on the specific visual task [92]. Overall, the way spatial information was digitally presented not only influenced performance but also manifested in neural responses, as evidenced by the analysis of Event-Related Potentials (ERPs).

The impact of the third dimension in images was already evident in the brain activity linked to attention allocation and early information processing in the occipital and parietal regions. However, the observed effect size was relatively small for both displays, likely due to the subtle differences in disparities between the search items. In essence, our current experimental findings build upon prior research, supporting the idea that disparities in information between three-dimensional and two-dimensional images manifest in early neural activity [68][69][70] [71][72][73][78].

It's worth noting that the early perceptual sensitivity of Event-Related Potentials (ERPs) to depth defined by disparities has been reported not only for digital images [68][71][72][73] [78], but also for real objects [103]. Additionally, early cognitive responses did not show variation based on the type of disparity [78] or the presence of consistent depth cues [82]. Taken together, these findings suggest that early information processing remains consistent regardless of the specific features within a dimension. Since the observed effect was similar for both displays in this thesis, the results offer new evidence that this response invariance extends to the type of depth visualization.

The P1 and P2 components exhibited a higher amplitude in scenarios where the target was absent across all five electrode sites. This amplitude variation could be attributed to increased stimuli brightness, as suggested by [79][80]. Nevertheless, this discrepancy in amplitude cannot be solely attributed to brightness levels. Contrary to expectations, the waveform results indicate that the amplitude of P1 and P2 for target-present (3D) volumetric stimuli is lower than for target-absent (2D) anaglyph stimuli, even when brightness levels are higher. This suggests that, in addition to physical stimulus properties, the primary assessment of depth occurs within the P1 and P2 components. Moreover, the observed higher amplitude during non-target presentation compared to target presentation in the P3 component is likely due to the brain's response to the extraction of depth information, as proposed by [74].

During the second time window (70-180 ms) following the onset of the visual search array, hemispheric activation exhibited variability when comparing the brain's response to both displays. This observation could be linked to the processing of features and spatial location, as noted in studies by [104] and [76]. Given that increased amplitudes of Event-Related Potentials (ERPs) are associated with superior performance in feature-based stimulus processing, as indicated by [105], we propose that less effort was required when the visual search array was presented on the volumetric display. Consequently, the volumetric representation of information may lead to a quicker cognitive response compared to the superimposition of two images using a stereoscopic approach.

Several studies employing anaglyph-based and polarization-based approaches to create three-dimensional visual stimuli have reported the dominance of the right hemisphere [71][72][74]. These studies suggested that differences in cortical activation reflected the processing of stereoscopic disparity. However, in line with findings from other studies [70][76], we did not observe any systematic asymmetric responses specifically associated with three-dimensional images. Consequently, the question remains open regarding whether the dominance of the right hemisphere can be attributed to the processing of binocular disparity, or the way visual inputs are separated for both eyes.

The primary factor contributing to differences between the two visualization systems could be the existence of an accommodation-vergence conflict during anaglyph image presentation. Numerous studies have highlighted the impact of accommodation-vergence conflict [82][99][106] as a significant factor in activating components in response to stimuli. This conflict may also influence the P3 component within the time window of 250-400 ms. Analysing the waveforms reveals that the highest amplitude of P3 is associated with non-target anaglyph, followed by non-target volumetric. The greater amplitude of non-target volumetric compared to target anaglyph suggests that our brain prioritizes depth detection over accommodation-vergence conflict. As a result, the non-target experiment exhibits a higher amplitude of P3. In contrast, the target experiment displays a higher amplitude in volumetric visualization than anaglyph. This discrepancy may indicate that consciousness of the volumetric image is more straightforward than that of the anaglyph image, as suggested by [47].

Significant differences related to the type of depth visualization emerged later in the analysis. In comparison to volumetric images, stereoscopic images elicited more pronounced negative activity in the parietal region during the 250-400 ms period following the onset of the visual search array. Given that a similar phenomenon was not observed for two-dimensional images, we propose that this finding may be linked to the integration of visual inputs for perceptual decisions regarding the third dimension of the image.

The cognitive process of depth perception involves the complex integration of information. Stereoscopic input can modulate high-level perceptual processes associated with view generalization [72], figure-ground segmentation [75], classification [72], and recognition of visual information [71]. Furthermore, in comparison to early processing stages, high-level perceptual processes leading to image classification and information recognition appear to reflect the specifics of three-dimensional visual stimuli. Notably, differential sensitivity of Event-Related Potentials (ERPs) was observed for crossed and uncrossed disparities [78]. Uncrossed disparities resulted in larger negative deflections, suggesting that identifying uncrossed disparities demands more attentional resources and effort than identifying crossed disparities. Other studies reported correlations between ERP amplitudes and differences in depth cues between inputs for the two eyes [76][107].

Comparing neural responses to stereoscopic images with varying disparities, larger negative deflections were evident for images with disparities beyond the zone of visual comfort [82].

Consequently, 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 information may impose greater cognitive demands, potentially leading to a faster onset of fatigue in the long term [86][87], 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 [101][108], 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. Despite these limitations, the current results establish a useful foundation for further research on three-dimensional visual search. They underscore the necessity for a comprehensive assessment of neural indicators related to user experience and performance in the context of novel visualization systems. Subsequent investigations are needed to validate these findings using different visualization systems.

5.2 Brain activity when viewing crossed and uncrossed 3D anaglyph image

Considering the 3D structure of the world, depth perception is a vital visual task performed daily. Depth perception can be achieved through both monocular and binocular cues. However, binocular disparity is a potent cue in 3D perception, relying on the difference in retinal images arises from the horizontal separation of the eyes, necessitating the brain to merge the 2D images to perceive a single 3D image [109][110].

The presence of neurons responsible for binocular processing has led to various studies investigating cortical activity during binocular disparity. However, few studies have explored the effect of each type of disparity on brain activity. Given that crossed and uncrossed disparity are processed by different cortical neurons in the brain [56][111], 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 in brain activity.

This question is the focus of the current study, which aims to analyse brain activity components and performance during crossed and uncrossed disparity. For the research, 3D anaglyph images were presented on a flat-panel display, and both disparities were presented in a zone of comfort to avoid accommodation-vergence conflict. The results of the study showed some differences in perception between the two types of disparities.

The analysis of response time and accuracy rate demonstrated a quicker response with higher accuracy in crossed disparity, suggesting that crossed disparity is easier to perceive than uncrossed. This is supported by the study by [112], which concluded a higher preference for near objects than for far objects. However, based on statistical analysis, no significant difference was found in either performance component.

The parietal and occipital lobes of the brain were previously associated with binocular processing [67][70]. In the current study, both areas demonstrated a significant amount of activity during crossed and uncrossed disparity processing. The importance of the parietal and occipital lobes was also emphasized in studies based on 3D processing of depth perception highlighting the role of the parietal lobe in stereoscopic visualization. Since anaglyph display was used in the current study, it supports the conclusion of previous research.

The visible correlation between the two types of disparities in the N1 component could be associated with the requirement of discriminating between crossed and uncrossed disparity. This assumption is based on the study by [45], which stated the presence of the N1 component during attempts to discriminate stimuli, rather than just detecting their presence. However, no statistically significant difference was found for the N1 component in the current study, possibly due to the similar physical properties of both disparities. Additionally, considering the small number of participants, it is difficult to pinpoint the exact cause of the larger N1 in crossed disparity compared to uncrossed.

The larger amplitude in the P2 component during uncrossed disparity is likely due to higher attention demand during uncrossed disparity processing. This statement aligns with the results of the study by [113], which stated that higher attention is required during the switching from near to far locations. Furthermore, [114] concluded in their study that there is a correlation between task difficulty and high amplitude in the P2 component.

Previous studies have concluded that the amplitude of the P3 component is affected by conscious perception and confidence level [47][115]. The similarity in the amplitude of the P3 component in the current study could indicate a similar level of awareness and confidence. Additionally, the P3 component is associated with task difficulty and tends to increase during unfamiliar stimuli [38][114][116]. However, no significant difference among the visual stimuli was observed.

The analysis of theta waves revealed high activity in the frontal area of the brain for both disparities, which could be linked to participants being concentrated but relaxed during disparity recognition. This assumption is based on the studies by [117], as he concluded that frontal theta prevalence is present during a focused but relaxed state of mind. The correlation between increased theta and reduced alpha waves during uncrossed disparity could be associated with higher attention demand due to incorrect responses [118]. No significant difference was found in either of the waves.

Beta waves are involved in decision-making, focus, and logical reasoning. However, in comparison to high beta waves that provide information on stress level, the frequency of mid-range beta waves (15-20 Hz) is associated with increased task performance [119]. Based on this, the significant activity during crossed disparity could be related to a higher level of performance. Furthermore, the results of both response time and accuracy rate in this study support this idea.

This study faced some limitations, which need to be considered in further research. One of them is that gamma waves were not covered in this study, due to the simplicity of the visual tasks. Additionally, it is important to mention that the obtained results were based on a small sample group. A larger number of participants could influence the results; however, it is impossible to predict how exactly the results would change. Another limitation was the vertical body position during data recording since this could influence brain activity and cause noise in the recorded data. Furthermore, some human factors could also affect activity, such as blinking rate and highly active brain. Nevertheless, the current study is bias-free since the trials presented to the participants were randomized, excluding the possibility of guessing.

The quantitative research done in this thesis sheds some light on the differences in brain activity in the case of crossed and uncrossed disparity. However, further research with different task stimuli could provide information on gamma waves and give a deeper understanding of cortical activity during type-related disparity processing. This research could be useful in further assessments in similar studies.

5.3 Brain activity when viewing 3D vs 2D image on the volumetric display

In this experiment, cortical activity in the human brain was examined by analysing Event-Related Potentials (ERPs) and Power Spectral Density (PSD) across occipital and parietal electrodes in two distinct conditions: 2D and 3D perception of volumetric visual stimuli representation. The primary objective was to identify potential differences in the amplitude and latency of ERP components, as well as the amplitude of PSD in the alpha and beta bands under the two viewing conditions. Given the study's emphasis on volumetric display, the outcomes might unveil favourable aspects of the interaction between volumetric displays and the human visual system, particularly considering the absence of accommodation-convergence conflict in this investigation.

Behavioural data serves as a logical means to substantiate or refute a hypothesis. Previous research indicates that response time can function as a factor in visual target perception [120][121]. In this study, behavioural data, revealing a shorter response time in the 3D task, serves as compelling evidence supporting the notion that perceiving 3D images on the volumetric display is easier compared to 2D images, as also reported in [89]. Importantly, the study's time-free nature allowed subjects ample time and motivation to accurately perform the task.

The impact of the third dimension of the image manifested in brain activity associated with sensory resources and early information processing in the occipital and parietal regions within 50-100 ms after stimulus onset. Although the effect was subtle for both visual targets, potentially due to their similar physical properties and dimensions, a slight difference may indicate the involvement of early neural activity receiving feedback from higher-level processing locations [68][69][70][71][72][73][78][103]. Notably, early perceptual sensitivity of ERPs to depth was observed not only for digital images [68][71][72][73][74] but also for actual objects [103]. Moreover, early cognitive responses did not show variation based on the type of visual target [78] or the availability of consistent depth cues [122], suggesting invariant early information processing in response to within-dimension features.

The second time window (100-200 ms) corresponds to cognitive processes such as working memory, memory performance, and semantic processing [44][123]. Although no statistically significant difference was observed between the two types of images, a slightly higher activity in 2D image perception compared to 3D, as indicated by topographical maps and waveforms, may be attributed to the presentation of both visual targets in a sequence of trials, engaging memory to distinguish between the 2D and 3D targets. Additionally, the consistent P2 peak latency across all subjects and conditions implies equal attention and memory function involvement in visual data analysis by the visual cortex.

The P3 component, a dominant wave on the parietal cortical area observed around 250 ms after stimulus onset, is linked to decision making. In this experiment, a slightly higher amplitude of P3 associated with 2D perception was observed, though not statistically significant. However, a significant difference in P3 latency between the 2D and 3D conditions over the Pz electrode suggests that discriminating 2D stimuli on a volumetric display may pose a greater challenge for subjects engaged in 3D tasks. Interestingly, these results differ from those reported by [122], who found higher P3 amplitude in the comfort zone of virtual depth perception compared to the non-comfort zone.

Power Spectral Density (PSD) is a measure of signal power distribution over frequency, offering insights into how the brain responds to stimuli. PSD analysis indicated slightly higher amplitudes in the alpha and beta bands (though not statistically significant) during the 2D task, potentially reflecting additional processing demands required to discriminate 3D from 2D trials in the 2D experiment. Furthermore, an examination of parameters such as total power, spectral band power, and median and spectral edge frequency provides additional information about brain activity in response to stimuli.

5. 4 The impact of different lighting conditions on volumetric 3D perception

The primary objective in this study was to investigate how various lighting conditions and prolonged usage of a volumetric multiplanar display impact human neural processes, with a specific focus on analysing the amplitude and latency of the P3 component.

Lighting conditions, as a physical factor, significantly influence human visual perception. Previous research, such as Lim's study [124], indicated that 800 lux illumination led to a higher P3 amplitude for incorrect responses. Johannes [80] demonstrated that higher stimulus luminance resulted in increased ERP amplitudes. Additionally, various researchers have delved into the effects of mental and visual fatigue during extended display usage, with visual fatigue attributed to conflicts like vergence-accommodation in conventional 3D displays [83][125].

This study specifically evaluated the performance of a visual search task on a volumetric display under two different lighting conditions: photopic and scotopic. It was found that response times were significantly lower in photopic conditions compared to scotopic conditions. However, the difference between response times in the first and last tasks was not statistically significant. One interpretation could be that, when considering each lighting condition separately, there was a shorter response time in the last task than in the first, possibly indicating neural facilitation and adaptation to the task due to working memory. This contrasts with [126], which suggested that prolonged tasks increase response times, suggesting potential influences of motivation on results.

Another perspective to consider is that the photopic experiment followed the scotopic condition. The significantly shorter response time in the photopic condition might be attributed to learning the task and enhanced visual working memory since the photopic task was done after the scotopic task. [127].

The P3 component, appearing as a late positive wave at parieto-occipital sites, is often associated with the identification and assessment of stimuli. The peak amplitude and latency of P3 were investigated in this study. The significantly higher amplitude in the last task compared to the first may indicate heightened attention and engagement to discern the relative depth effect of the visual task [128], ruling out visual fatigue as a factor given the shorter response time in the last task. While some studies suggest a lower P3 amplitude during repeated tasks due to adaptation [40][126], others indicate larger P3 amplitudes for familiar attended or learned items [129][130][131].

Considering latency in ERP analysis is crucial, as higher latency may signal visual or mental fatigue or difficulty in decision-making. The peak latency was earlier in the photopic condition than in the scotopic condition, though the difference was not significant. This could be attributed to working memory, as the photopic experiment followed the scotopic condition. Notably, there was no difference in latency between the first and last tasks in the photopic condition. However, in the scotopic condition, there was a significantly earlier peak latency between the first and last tasks. This suggests that using the volumetric multiplanar display in scotopic conditions may facilitate the learning process, aligning with findings from [127].

6. Conclusions

The Thesis provided valuable insights into the cognitive processes and neural activities associated with different types of 3D visualizations. The thesis followed the potential of the EEG to assess the depth perception objectively. The findings suggest that the type of 3D visualization can significantly affect user performance and brain activity, with implications for ergonomics, user experience, and the design of future visualization systems. The study conducted an exploratory analysis of brain activity during the perception of 3D visual stimuli using different display technologies to investigate if EEG is enough sensitive to detect any changes during the depth perception. Specifically, the study compared stereoscopic visualization on a flat panel display with volumetric visualization on a multiplanar display. The findings revealed significant differences in late cognitive processes within the posterior regions of the brain, depending on the type of 3D visualization. The importance of evaluating the different visualization system is to understand the effectiveness of EEG signal recording and analysing in detecting objective depth perception in individuals as the main aim of the thesis is the application of EEG in objective assessment of 3D image perception on the volumetric display.

The study highlighted the importance of considering the physical attributes of images, visual perception, and attention when evaluating the ergonomics of displays. Both stereoscopic and volumetric displays effectively incorporated binocular disparity as a depth cue, leading to high search performance. However, the stereoscopic display resulted in longer completion times for the visual search task, indicating that the volumetric display may lead to quicker cognitive responses.

The study also investigated brain activity during the perception of crossed and uncrossed 3D anaglyph images. The results suggested that crossed disparity is easier to perceive than uncrossed disparity, as indicated by quicker response times and higher accuracy rates. The analysis of brain activity components revealed significant activity in the parietal and occipital lobes during both types of disparity processing.

Furthermore, the study examined brain activity during the perception of 3D versus 2D images on a volumetric display. The results showed that perceiving 3D images on the volumetric display was easier compared to 2D images, as indicated by shorter response times. The analysis of brain activity components revealed differences in the amplitude and latency of ERP components, as well as the amplitude of PSD in the alpha and beta bands, under the two viewing conditions.

Finally, the study investigated the impact of different lighting conditions on volumetric 3D perception. The results showed that response times were significantly lower in photopic conditions compared to scotopic conditions. The analysis of brain activity components revealed differences in the amplitude and latency of the P3 component, suggesting heightened attention and engagement in the photopic condition.

To sum up, the study provides valuable insights into the cognitive processes involved in 3D perception using different display technologies. The findings suggest that volumetric displays may offer advantages over stereoscopic displays in terms of user experience and performance. However, further research is needed to validate these findings and explore the potential long-term effects of using 3D visualization systems. Moreover, the further study is necessary to evaluate the brain activity of people with abnormal depth perception. It is beneficial to determine the active areas of the cortex while there is inability to perceive the depth.

The significance of assessing various visualization systems lies in comprehending the efficacy of EEG signal recording and analysis in detecting objective depth perception in individuals. The primary objective of the thesis is to apply EEG for the objective assessment of 3D image perception on the volumetric display. By comparing different visualization methods, the study aimed to determine EEG is a reliable tool for assessing depth perception. This is crucial for understanding the neural processes involved in 3D perception and for developing EEG-based methods for objectively measuring depth perception. The findings of this study will contribute to the development of more accurate and reliable methods for assessing 3D perception, which can be used in various fields such as vision science and visual ergonomic assessment.

7. Thesis

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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FUNDAMENTAL AND
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PROJECTS

10. References

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Appendix 1

Inform consent.

In the Department of Optometry and Visual Science, the human vision is being studied with the aim of gaining in-depth understanding of the functions and processes of the eye and visual system.

In the study, **non-invasive** methods are used – data are only obtained in form of responses to the visual stimulus.
It is the participant's responsibility (and the right) to inform the experiment operator before the study if:

1) he/she decides not to participate in the research. The participant is not obliged to explain the motives of his/her actions. If the participant wants, the study can be resumed later, but the participation in the study is a voluntary choice of the participant.
2) he/she should not drink alcohol 24 hours before the examination.

Anonymity. Vision studies collect only personal information. The provided personal information remains anonymous. For the purposes of the research, data (such as gender, age, profession, etc.) may be processed along with the answers provided to characterize the common trends, but the identity of the participant (including initials), whilst presenting the results of the study, always remains anonymous.

I am aware of the objectives and course of the study, as well as the methods of the research, and grant my permission to use the information and data provided by me for the purposes of the research.

Date: ________________________ ________________________
/Name, Surname/ /Signature/