Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Psychology

10013

Exploratory study: Relationship between Simulation Sickness and EEG measurments, and the potential sex discrepancy present in VR

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Supervisor: Sebastian Thorp
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Candidate 10013

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Supervisor: Sebastian Thorp

Acknowledgments

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During the project we received a lot of freedom, allowing us to focus on our own individual research questions. This allowed us to grow as students through teaching us to be more selfsufficient. Our Supervisor had done all the preliminary work for the laboratory work and processed the EEG information. Together with two other fellow student I was resonponsible for recruiting and communicating with participants. With great support and guidance from our studentassistant we performed the experiment. Here others in the group had the greatest responsibility. However, I also helped out in the lab when necessary. Two other of my fellow students were responsible to transfere the data collected into excel and SPSS. There was good teamwork within the group where we could discuss issues and helped each other when necessary.

Abstract

Negative side effects after exposure to Virtual reality, also known as Simulation Sickness (SS), has been revealed in previous studies. It could pose a problem for reaching the full potential of the VR technology. One must be able to quantify the effect SS has to fully understand and measure the negative effect. Articles tend to use the subjective measure Simulation Sickness Questionnaire (SSQ) from Lane and Kennedy (1993) to quantify SS. However, using a psychophysiological measure like electroencephalogram (EEG) provides an objective and potentially more accurate results. Previous studies have also revealed that user experience with SS is not uniformly, SS is more frequently reported by women than men. The exploratory studies aim is to examine the potential for EEG to be an alternative measurment of SS and if brain activity can be used to show or explain the potential sex discrepany present in VR.

To examine the explanatory effect of EEG for SS a pearson correlation was performed. T-tests were performed to investigate the group differenece between men and women for SS and brain activity.

A significant moderate to strong correlation was found between total SS score and brain activity for most regions at all frequencies, except for the occipital-right lobe in the alpha frequency. No significant difference was found between the sexes for SSQ scores or brain acivity. The results indicate that EEG measures is a good objective alternative to measure SS instead of the SSQ which is influenced by the participants judgement.

Exploratory study: Relationship between Simulation Sickness and EEG meaurments, and the potential sex discrepancy present in VR

Virtual reality (VR) is an environment near reality created by computers to immerse the user in a new world (Rangelova et al., 2020). Increased use of the technology has revealed that the user can experience negative side effects. The negative effects is caused by VR`s influence on human's physiology causing symptoms like dizziness, nausea, sweating and headaches (Grassini & Leumann, 2020). These symptoms are often related to Simulation Sickness (SS) and a negative experience with VR (Rangelova et al., 2020). SS can be caused by a sensory integrating problem often referred to as vection, perception of movement created by solely visual input, or nonsynchronous visual and vestibular sensory input (Chang et al., 2020; Keshavarz et al., 2015).

To fully understand and measure the negative effect that simulation sickness has on the development of VR one needs methods to quantify it. However, quantifying SS is difficult due to the limited availability to systematic approaches to evaluate SS continuously. Articles tend to use the Simulation Sickness Questionnaire (SSQ) by Lane and Kennedy (1988). One of the issues with the questionnaire could be that it is subjective where the measurements are based on the participants perception of their state. A subjective measure of SS is problematic since it could not be generalized to the whole population as effectively that an objective approach could (Chang et al., 2023).

A way to solve these issues could be to use psychophysiological measures that provide objectivity. By then additionally using electroencephalogram (EEG) measurements to record electrical activities in the participant`s brains one could possibly reduce the subjective side effects measured, providing a greater level of accuracy (Im et al., 2018). Possibly making it a more reliable measure than the subjective experience of SS. Compared to other physiological measures of SS, respiration and skin conductivity, EEG can for example instantaneously measure changes in activity related to pain signals (Chang et al., 2023). With pain being a subjective sensory experience such as SS and EEG a surrogate marker of brain activity (Assenza & Lazzaro, 2015; Bromm, 2001). The EEG recordings could help solve the significant obstacle SS is for the future development of VR technology (Grassini & Leumann, 2020). The discomfort can often also be referred to as cybersickness or VR sickness. The terminology simulation sickness, with the abbreviation SS, will be used to refer to all these terms.

It has been shown that a majority of individuals at least experience a moderate level of SS during or after using VR (Krokos & Varshney, 2021). User experience is not uniformly. A study by Munafo et al. found that woman are two to three times more likely to report SS (2017). Usability issues such as SS impairs the potential of VR and finding a solution for this issue is important for further development of the technology. One cannot have technology created for one gender and not another, in other words one cannot have “sexist” technology (Pröbster & Marsden 2021). Having “sexist” technology could make it more difficult for women to emerge in the world of technology reducing their access to related fields. Through having gender inclusivity one could potentially fully employ VR’s potential (Pröbster & Marsden 2021).

The terminology “sexist” VR is not aimed towards the producers and their intentions when developing the technology. The reference is aimed at indicating that the technology favours one sex over the other (Grassini & Leumann, 2020). One has seen a trend that men have a tendency to underreport their symptoms of discomfort and woman to overreport, which could be a potential explanation for the gender imbalance of SS (Rangelova et al., 2020). Therefore, EEG may reflect an objective measure of SS to circumvent such differences in subjective reporting.

In this article the focus will be on if SS from VR could be demonstrated through brain activity, and further if it could help to show and explain the sex differences of SS in VR. The brain activity is measured through EEG measurements. More research is needed in the field since there is limited information on SS and brain activity.

Theory

Virtual reality

VR is an environment near reality created by computers to immerse the user in a new world. There has been a rapid increase of interest towards VR over the last couple of years which is related to the greater accessibility through the development of technology, ease of use and affordability (Rangelova et al., 2020). With VR being one of the newest developments in technology it is being more commonly used in the entertainment industry, within research and even the medical field (Grassini & Leumann, 2020). It creates situated or realistic environments for different purposes, like learning, that are exempt from liability issues, danger and high costs (Rangelova et al., 2020). The terminology VR is used for a range of technologies, both hardware and software. With the development of the first Head Mounted Display (HMD) VR technology became accessible for the population allowing it to be widely used in training and research (Jensen & Konradsen, 2018).

VR technology can be immersive where one is surrounded by the environment. Immersion are the technical aspects of the VR technology that influences ones experience to create a sense of presence. However, a high immersion could also cause notably higher SS. HMD provides immersion through having an internal and individual view of the environment created by VR (Jensen & Konradsen, 2018; Wu et al., 2020). The headset in HMD can be powered through different hardware (smartphone, PC or game-console) or be stand-alone where additional hardware is not necessary. The HMD-users have two controllers allowing them to interact with the three-dimensional environment created (Duzmańska et al., 2018).

Simulation Sickness

SS is known as a form of visually induced motion sickness, since the main source of sensory input causing the motion sickness is visual stimuli. (Munafo et al., 2017; Rangelova et al., 2020). The type of motion sickness is often related to the interaction with a virtual environment (Duzmańska et al., 2018). The primary senses that are involved in SS are the vestibular and the visual systems, and their integration (LaViola Jr., 2000). Motion sickness is a sensory mismatch mainly between visual, vestibular and sensory-motor information in the presence of movement (Laessoe et al., 2023). Motion sickness differs from SS through that it can be induced when only vestibular stimulation is present, and SS could be induced through solely visual stimulation. The distorted visual-vestibular relationship, a visual stimulus being present creating perception of self-motion without a vestibular stimulus, creates the basis for the Sensory Conflict Theory (LaViola Jr., 2000). The Sensory Conflict theory is the oldest and most accepted theory for SS. It states that the false motion perception in VR disrupts the established interplay of the senses causing sensorial conflict (Wienrich et al., 2022). There are two other central theories about SS: the poison theory and the postural instability theory. The former theory would be an evolutionary explanation for SS. It suggests that the disruption of the coordination of sensorial input systems is misinterpreted as ingestion of poison causing physiological side effects. The latter theory is based on the belief that the goal of humans is to keep postural equilibrium in its environment. The environment in VR disrupts the equilibrium causing postural instability over a significant period of time (LaViola Jr., 2000).

The severity of SS may be proportional to the time exposed to VR (LaViola Jr., 2000). Symptoms normally seen in SS could be disorientation, postural instability, nausea, fatigue and headache. These symptoms can develop during exposure or take some time to develop after exposure (Grassini & Leumann, 2020). The effects of SS could cause potential danger through the inability to perform everyday tasks because of SS lasting up to several days (Kim et al., 2005). However, research has shown that habituation to SS does occur when exposed to VR. (Kim et al., 2005; LaViola Jr., 2000, Grassini & Leumann, 2020). Meaning that previous experience or exposure to VR could reduce the level of SS experienced.

Simulation sickness in women

A study by Flanagen and collegues (2005) reported a sex difference for reported visually induced motion sickness, where visually induced motion sickness was two times as often reported by women than men. Motion sickness results are often generalized to SS due to the close connection between the two phenomena. The trigger of SS symptoms and the sex imbalance is not known, however there are different theories being tested (Grassini & Leumann, 2020). Clemes and Howarth (2005) theorised that the hormone levels in the menstrual cycle could be an explanation. They found that women were more prone to develop SS symptoms on day 5, 19 and 26 in their cycle, and suggested that it could be explained by the female sex hormone oestradiol. The short lifespan of the increased sensitivity towards SS in woman was criticised. Other theories for the sex difference of SS was that women on average have a larger field of view than men and the physical differences between sexes (Grassini & Leumann, 2020). Field of View is the development of a visual world (Emery & Camps, 2017). A greater field of view makes the user more sensitive to visual information and would receive more perceptual information causing vection and a greater sensitivity to flicker. Flicker can induce a greater level of eye-fatigue which is connected to the development of SS (LaViola Jr., 2000). The theory of sexual dysmorphism suggests that there is a difference between the sexes' postural stability where woman have a greater instability of movements (Grassini & Leumann, 2020). Relating the sexual dysmorphism with the postural instability theory it would suggest that woman are more susceptible to SS. The observation that women scoring higher when reporting the level of discomfort during a VR experience could also be explained through men under-reporting and women over-reporting symptoms of discomfort (Rangelova et al., 2020).

Electroencephalogram

EEG is a neural imaging technique that allows us to examine electrical activity in the brain, also known as brain activity (Naqvi et al., 2014). Brain activity is often regarded as energy use in the brain. The energy is mainly used by excitatory synapses, but is the sum of both inhibitory and excitatory processes (Attwell & Laughlin, 2001; Buzsáki et al., 2007). Cortical neurons which mainly are concentrated in the cerebral cortex is the main EEG source. The perpendicular direction of the neural current is caused by the perpendicular location of the apical dendrites. From the two intracellular potentials that help generating EEG signals the postsynaptic potential creates greater EEG signals than action potentials due to that more neurons fire synchronously (Im et al., 2018).

The method of measuring EEG prevail from 1924 when the German psychiatrist Hans Berger measured the first human EEG (Im et al., 2018). The rapid technological development within the field of neuroimaging allows one to study the brain activity during SS experiments (Chen et al., 2010; Bromm, 2001). Studies have shown that EEG's high level of temporal resolution allows researchers to examine the change in neural activity instantaneously (Chen et al., 2010; Bromm, 2001). In EEG the electric potential difference between electrodes over time is measured. For this at least two electrodes must be present. The electrodes can be invasive where the EEG signals are measured inside the skull, or noninvasive where the electrodes are connected to the surface of the head or inside a cap (Im et al., 2018). Study by Ball and colleagues (2009) has shown that the signals from invasive EEG have a much greater quality than non-invasive. However, non-invasive EEG such as the one being performed in this study is more accessible through being safer (Ahmadian, 2013).

The advantage of using EEG over other types of neuroimaging for analysing the relationship between SS and brain activity, such as positron emission topography and functional magnetic resonance imaging, is that it has a high temporal resolution, is economical and one is not exposed to radiation or a high magnetic field. However, the depth and spatial resolution in the other mentioned imaging methods surpass that in EEG (Im et al., 2018).

The waves that the EEG records can be divided into five different frequency bands: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz) and gamma (>30 Hz). The wave frequencies are related to different forms of brain activity (Naqvi et al., 2014). Delta waves are typically associated with rest and the reduced attention to the physical world, and theta waves are commonly seen in relaxed states with little brain activity and often categorized as slow activity (Naqvi et al., 2014; White & Richards, 2009). Enhanced theta is often also associated with accuracy and successful memory (Herweg et al., 2020). Alpha waves are related to relaxed states with closed eyes, and often seen as a connection between the conscious (external) and the subconscious (internal). Beta is seen during intense brain activity and associated with processing information, and gamma could be seen during problem-solving and often related to memory (Naqvi et al., 2014; White & Richards, 2009).

Electroencephalogram data and Simulation Sickness

Several studies have tried to investigate the relationship between brain waves frequency bands with the presence of SS. This relationship could show what type of brain activity is related to SS and could possibly explain the correlation between them. This would potentially be important since it could mean that EEG can be a reliable alternative measure of SS. Studies have differentiating opinions of the direction of the relationship between the alpha frequency and SS. Where some studies say that when SS is high there would be a higher alpha power in this condition (Ahn et al., 2020; Chen et al., 2010; Krokos and Varshney, 2022; Lin et al., 2007; Oh and Whangbo, 2018; Kim et al., 2019). Other studies have shown that alpha power is decreased in a condition where simulation sickness was reduced (Celikcan, 2019; Chang et al., 2013; Choi et al., 2009; Liu et al., 2020; Mawalid et al., 2018). For the delta frequency, studies have found that activation in the delta frequency is enhanced in more severe SS conditions showing a positive correlation between the variables. (Chang et al., 2013; Choi et al., 2009; Kim et al., 2005; Krokos and Varshney, 2022). Similarly to the alpha frequency studies have different results regarding the direction of the correlation for the theta frequency and SS. Where some articles found a positive correlation between activity in the theta band and SS (Chang et al., 2013; Heo and Yoon, 2020; Krokos and Varshney, 2022; Oh and Whangbo, 2018), and other articles present a negative correlation (Choi et al., 2009; Naqvi et al., 2015).

Most studies did not specify areas that activation was particularly enhanced when participants experienced SS. However, a study by Kim and colleges (2005) showed that SS is related to an increase in delta power and a decrease in beta power in frontal and temporal areas (F3 and T3 electrodes).

Objective of the present study

Studies have found that it is probable that SS hinders the potential and impairs the technological development of VR (Grassini & Leumann, 2020). Through being able to quantify SS accurately one could be able to oversee and understand the issue of SS. EEG provides an objective measurement offering a greater level of accuracy than subjective measurements that are influenced by ones judgment, like the SSQ (Chang et al., 2023). The present study examines the relationship between SS and brain activity, and if brain activity could show or explain the reason for sex differences in SS for VR. Articles have reported inconsistent results when it comes to the relationship of EEG measurements. Previous studies have reported a sex imbalance for SS, where women tend to report SS more often (Flanagen et al., 2005).

The research questions the study explores are: 1) Is there a correlation between SS and brain activity in VR? 2) Could a relationship between SS and brain activity then explain or measure the potential sex difference of SS?

Method

Participants

The study included 32 participants that mainly consists of students from the Norwegian University of Science and Technology (Trondheim, Norway). These participants were collected through convenience sampling. Name and email was collected when scheduling participants. All participants reported no previous history of epilepsy and had normal or corrected to normal vision. Around 10% of the participants seem to have misunderstood the corrected vision question. These replies were corrected based on that all participants were informed in the sampling process that normal or corrected to normal vision was required. Inclusion criteria for age of participants was set at 18 to 30 years old. Previous to performing the study the Norwegian Data Protection Agency (NSD) accepted the studies proposal.

The final analysis included 29 participants, since three were excluded. For two of the participants EEG data was missing (ID = 2 and 5) and the third participant was excluded due to technical issues (too much noise present in the data causing it to be an outlier) (ID = 32). The resulting sample consisted of 29 participants (12 women, 17 men) with an average age of 22.86 (*SD* = 1.36). The response rate could not be investigated as the number of participants asked to participate or cancellations that occurred was not measured.

Virtual Reality Environment

The VR environment consists of a seven-by-seven grid with six objects placed around. The setup of the VR environment can be seen in figure 1 below.

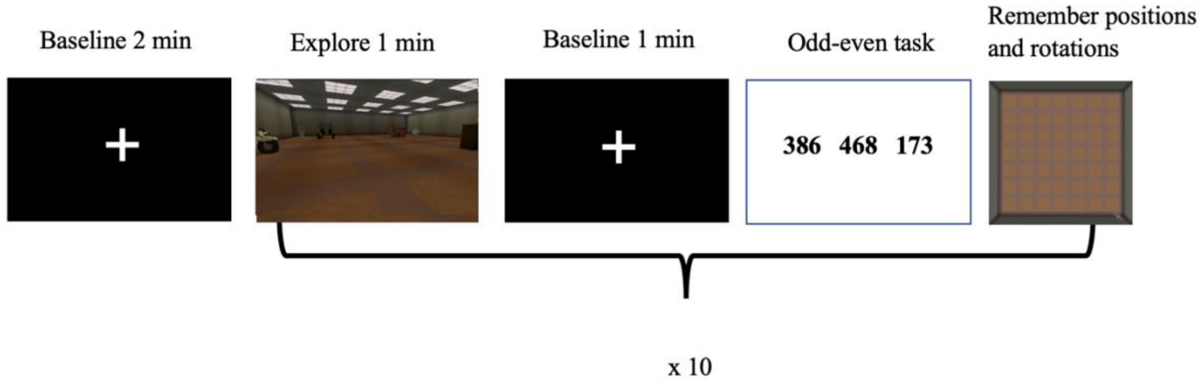
Figure 1

Minecraft Virtual Environment

Note. Figure 1 is a visual representation of the setup of the virtual environment the participants interacted with.

The participant has one minute to remember the placement of the objects on the grid before being transported into a black room for one minute and then having to perform an odd-even task before recollecting and placing the objects on the grid. An odd-even task is performed to free up the working memory by causing a disruption, in order to measure allocentric processing instead of the capacity of the working memory. The participants were seated during the whole experiment. The VR experience is of a single modality as it only uses visual input and not vestibular. In Figure 2 the study design's outline is presented.

Figure 2
Study design



Note. Figure 2 represents the sequence the experiment consisted of.

Command blocks were used to create the system in the VR that teleported the participants between the different environments. A Redstone block was created for specific coordinates to start this sequence of teleportation between the environments.

The PC used to power the HMD was an Intel i7 8086K (processor) with a 1080 ti graphic processing unit from Nvidia. It has a 1080p monitor with 60 Hz and uses Windows 10.

Procedure

Participants were asked to fill out a consent form and an assessment of Liability whilst in the waiting area for the experiment. A short description of the experiment's procedure was given and participants were reminded of their ability to stop the experiment at any given point in the procedure. In the experiment room the participants were fitted with the EEG-caps and the HMD before the experiment started. For the HMD each participant adjusted the interpupillary distance of the goggles. Before starting the actual experiment the participants were instructed on how to navigate in the environment and how to control the controllers in a training environment. The joystick on the right controller was used for walking, and for looking around the joystick on the left controller could be used or the participant could look around by moving their head.

EEG recording segments were created for when the participant was in the simulation and when recollecting the placement of objects. All participants were naive to the task prior to the experiment. After the participants had completed the experiment they answered the SSQ. The questionnaire results and EEG data were manually transferred into SPSS and excel.

Measure – Simulation Sickness Questionnaire

The self-reporting Simulation Sickness Questionnaire (SSQ) by Kennedy et al (1993) provides a subjective assessment of the physical symptoms for SS. It consists of 16 questions where the answers range from 0 to 3, where 0 is do not feel anything and 3 is severely sick. One can calculate the total SS score or for the three different subscales: nausea, oculomotor and disorientation. To find a score the results are added together and multiplied by predetermined weights (nausea: 9.54, oculomotor: 7.58, disorientation: 13.92, and total SS score: 3.74) (Kennedy et al., 1993). For the present study the questionnaire was completed at the end of the experiment and not twice as suggested by Kennedy et al. (1993). This was done due to the priming effect the pre-test exposure of SSQ could have on the post-exposure test results (Young et al., 2006).

Apparatus

Virtal Reality System

The Oculus Quest 2 HMD is a PC-powered VR with 64 gigabits storage. It features a singular LCD panel with a resolution of 1832 x 1920 pixels per eye, and has a XR2 Qualcomm processor and a RAM of 6 gigabits. The field of view produced by the HMD is 89°. Oculus Quest 2 uses two touch controllers with hand tracking technology (for further information use the company website: https://www.meta.com/no/quest/products/quest-2/).

EEG

A unipolar configuration with 64 electrodes was used for the EEG analysis. The EEG cap's electrodes were placed after the international 10-20 system, with reference to the CPz electrode and used AFz as the ground electrode. To record electroencephalographic activity the ANT Neuro EEGO sport amplifier sampled at 512 Hz was used. Silicone was used as the conductive gel between the scalp and the electrodes, and to keep the scalp impedance as low as possible.

Pre-processing of Electroencephalogram data

The data for participants exposed to VR was processed with the software Matlab (R2023a) and the EEGLAB toolbox. Makatos preprocessing pipeline was used to create the script for the spectral analyses. The data was re-sampled from 512 Hz to 128 Hz. The data was filtered with a high and low pass filter with EEGLAB`s function “pop_eegfiltnew”. The remaining data ranged between 1-40 Hz. The “clean-rawdata” function in EEG lab was used in the first step in the cleaning of the data. Here abnormal data frequencies and electrodes based on average is removed and replaced with new generated data. The data kept was separated from the continuous data (per person: 10 x 1 min VR exposures). The second stage in the data cleaning process the “pop_runica” function in EEG lab was used. It involves identifying non brain activity through comparing ones data with reference data of brain activity based on “large data” machine learning. The function “IClabel” was used to remove data the algorithm with 80% certainty meant was not brain data. Data from two participants was removed: participant 2 due to the lack of EEG data recordings from the first three environments and participant 5 as the PC charger was plugged in and produced a lot of noise.

Data analysis

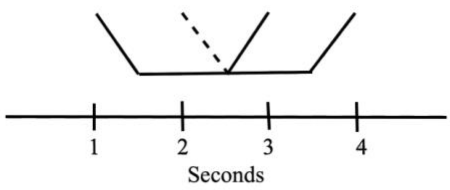
When screening the results from the SSQ there were missing data from one participant for one item. To fill this missing information a multiple imputation was performed. Multi imputations are generated probable values to fill missing information in a dataset (Li et al., 2015). Each probable value that is generated includes different estimations of the value missing (Kang, 2013). A linear scale model was used with five imputed data sets. The number of imputations was chosen after the MI theory and due to little missing data (Rubin, 1987). The results were pooled finding a mean imputation of 1.

Statistics

Spectral power was calculated for every electrode and frequency throughout the experiment with the “specto” function in EEGLAB. This provides one with a power-value (Watt/Hz). The average Power Spectral Density was calculated for 2 second windows with 50% overlap, called a hamming window, for every whole frequency. The average Power Spectral Density for the electrodes were grouped together. The Hamming window is represented in figure 3.

Figure 3

Hamming window.

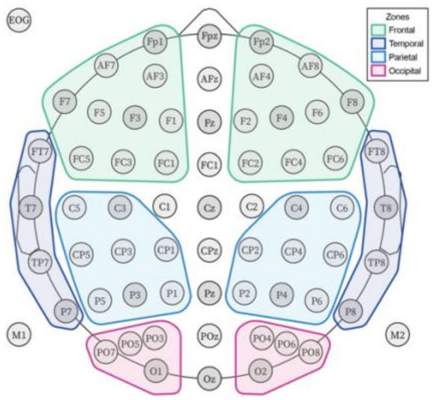


Note. Figure 3 visually represents how the Power Spectral Density was calculated for every 2 seconds with a 50% overlap.

Due to the inconsistency in results from previous studies an exploratory approach will be taken in the analysis. The grouping method is based on the method used in the article “The Neural Responses of Visual Complexity in the Oddball Paradigm: An ERP Study” by Hu and colleagues (2022). Where the spectral power recorded from the electrodes are grouped after the lobes (frontal, temporal, parietal and occipital), left and right, and for frequency (theta, delta and alpha). This allows one to provide more data and research on what areas that would be more involved in the occurrence of SS. The voltages of the electrodes in the group were pooled to find the group average for the area in question. The midline channel electrodes are not included in the analysis. The outline of the grouping of electrodes are presented in figure 4.

Figure 4

Grouping map of electrodes



Note. Figure 3 presents the grouping map of the electrodes. The scalp was divided into 8 groups: left frontal (Fp1 AF3, AF7; F1, F3, F5, F7, FC1,FC3, FC5), right frontal (Fp2, AF4, AF8, F2, F4, F6, F8, FC2, FC4, FC6), left temporal (FT7, T7, TP7, P7), right temporal (FT8, T7, TP8, P8), left parietal (C3, C5, CP1, CP3, CP5, P1, P3, P5), right parietal (C4, C6, CP2, CP4, CP6, P2, P4, P6), left occipital (PO3, PO5, PO7, O1) and right occipital (PO4, PO6, PO8, O2) (Hu et al., 2022).

Results

The statistical analyses were performed in the software IBM SPSS 27. The significance level for the analyses was set to p = .05.

Correlation between Simulation Sickness and brain activity for different frequencies

To investigate the relationship between SS and brain activity in the different regions, a Pearson`s correlation was conducted with the total SS scores and EEG data for the three different frequencies (theta, delta and alpha). The average total SS scores were 50.57 (*SD* = 34.08).

Table 1. Correlation Coefficient for the Studies Variables. (Total SS score – theta) (N=29)

Variable	M	SD	Total SS score	*p*
1. Total SS score	50.57	34.08	---	
2. frontal-left	4.56	7.91	-.39*	.034
3. frontal-right	4.63	7.63	-.52**	.004
4. temporal-left	4.08	7.20	-.48**	.008
5. temporal-right	5.30	6.13	-.51*	.005
6. parietal-left	2.18	9.15	-.47*	.011
7. parietal-right	2.97	7.84	-.55**	.002
8. occipital-left	2.16	9.72	-.47**	.010
9. occipital-right	2.01	8.22	-.37*	.047

Note. * indicates $p < .05$. ** indicates $p < .01$.

There was a significant, $p < .05$, negative correlation between total SS score and brain activity for all eight regions in the theta frequency. Where the negative correlation ranged from moderate to strong.

Table 2. Descriptive Statistic and Correlation Coefficient for the Studies Variables. (TS – delta) (N = 29)

Variable	M	SD	Total SS score	*p*
1. Total SS score	50.57	34.08	---	---
2. frontal-left	14.03	8.43	-.40*	.032
3. frontal-right	14.31	8.32	-.50**	.005
4. temporal-left	13.21	8.09	-.45*	.015
5. temporal-right	14.11	7.25	-.52**	.004
6. parietal-left	11.19	10.14	-.46*	.012
7. parietal-right	11.76	9.00	-.53**	.003
8. occipital-left	10.56	10.57	-.45*	.016
9. occipital-right	10.35	9.30	-.41*	.026

Note. * indicates $p < .05$. ** indicates $p < .01$.

Table 2 shows a significant, $p < .05$, negative correlation between the total SS score and brain activity in the regions. The correlations ranged from a negative moderate correlation to a strong correlation in the alpha frequency.

Table 3. Descriptive Statistic and Correlation Coefficient for the Studies Variables. (TS – alpha) (N =29)

Variable	M	SD	Total SS score	*p*
1. Total SS score	50.57	34.08	---	---
2. frontal-left	-1.48	7.58	-.40*	.034
3. frontal-right	-1.16	9.58	-.51**	.005
4. temporal-left	-1.16	7.13	-.49**	.007
5. temporal-right	-1.78	8.45	-.45*	.013
6. parietal-left	1.28	5.64	-.48**	.009
7. parietal-right	.29	6.45	-.54**	.002
8. occipital-left	-.01	7.40	-.46*	.011
9. occipital-right	.09	7.27	-.32	.088

Note. * indicates $p < .05$. ** indicates $p < .01$.

For the alpha frequency there is a moderate to strong significant, $p < .05$, negative correlation between total SS score and brain activity in all eight regions except of the occipital-right region. The occipital-right region has a non-significant, $p = .088$, moderate negative correlation. Across the three frequencies the parietal right has the strongest negative correlation with total SS score.

Sex differences

To examine the sex difference in SS and brain activity Independent two-tailed t-tests were performed. Independent two-tailed t-tests were chosen since the groups are mutually exclusive and as the research question is not directional. The disadvantage of performing several t-tests is that a family-wise error rate could arise. However, one tends not to use ANOVA since it is most commonly used when comparing the means of three or more groups. Further, compared to ANOVA with t-tests one would receive an unique *p*-value meaning that a multiple comparison would not be necessary (Mishra et al., 2019).

Simulation Sickness

To assess the deviations in SS between the sexes independent two-tailed t-tests were performed comparing the nausea score, oculomotor score, disorientation score and total SS score from men and women.

Table 4. Sample Descriptive Using t-test for Equality of means (N = 29)

	Men		Women		
	M	SD	M	SD	t-test
Nausea	44.89	32.13	38.16	40.06	.620
Oculomotor	38.79	23.04	68.85	101.21	.244
Disorientation	55.68	36.50	54.28	39.41	.922
Total SS score	48.65	31.40	53.30	38.84	.725

Note. M = mean, SD = standard deviation

Table 4 shows the difference in means for men and woman for the SS subgroups (nausea, oculomotor and disorientation) and total SS score. No significant difference in means was reported between men and woman for SS in VR. Men had higher SSQ scores than women for nausea and disorientation (nausea: ΔM = 6.73; disorientation: ΔM = 1.40), but women had higher SSQ scores for oculomotor and total SS score (oculomotor: ΔM = 30.06; total SS score: ΔM = 7.44).

Brain activity for different frequencies

Independent two-tailed t-tests were also performed to examine if a difference in brain activity in the different regions (EEG-data) could be seen in men and woman

Table 5. Sample Descriptive Using t-test for Equality of means (theta) (N =29)

	Men		Women		
	M	SD	M	SD	t-test
Frontal-left	4.33	8.43	4.89	7.47	.854
Frontal-right	3.97	7.81	5.58	7.59	.585
Temporal-left	3.62	7.24	4.74	7.41	.687
Temporal-right	4.46	6.02	6.49	6.35	.389
Parietal-left	.72	9.50	4.26	8.61	.313
Parietal-right	1.83	7.51	4.60	8.34	.358
Occipital-left	.15	9.20	5.00	10.11	.191
Occipital-right	.13	8.01	4.68	8.09	.145

Note. M = mean, SD = standard deviation

The mean difference between men and woman for brain activity for different regions (frontal-left, frontal-right, temporal-left, temporal-right, parietal-left, parietal-right, occipital-left and occipital-right) for the theta frequency is displayed in table 5. There was no significant, $p > .5$, difference between men and women in brain activity. Women had a higher power-value (Watt/HZ) than men, where the greatest difference was for occipital-left (ΔM = 4.85) and the smallest difference for the frontal-left (ΔM = 0.56).

Table 6. Sample Descriptive Using t-test for Equality of means (delta) (N = 29)

	Men		Women		
	M	SD	M	SD	t-test
Frontal-left	14.06	9.00	14.00	7.95	.984
Frontal-right	13.76	8.46	15.08	8.42	.683
Temporal-left	12.92	8.02	13.62	8.54	.824
Temporal-right	13.21	7.10	15.38	7.58	.437
Parietal-left	9.72	10.40	13.28	9.82	.361
Parietal-right	10.50	8.60	13.55	9.62	.379
Occipital-left	8.08	10.17	14.08	10.54	.135
Occipital-right	8.43	8.71	13.07	9.80	.191

Note. M = mean, SD = standard deviation

That the mean difference in brain activity in different regions for the delta frequency for men and women is not significant, *p* > .5, is presented in table 6. The mean brain activity is higher in all brain regions in woman than men except in the frontal-left lobe. The greatest mean difference for brain activity in men and woman is in the occipital-left (ΔM = 6.00) and the smallest difference in the frontal-left (ΔM = 0.06).

Table 7. Sample Descriptive Using t-test for Equality of means (alpha) (N=29)

	Male		Female		
	M	SD	M	SD	t-test
Frontal-left	-.14	7.72	.42	6.91	.843
Frontal-right	-.68	7.37	.94	7.66	.573
Temporal-left	-.38	6.55	1.25	6.47	.514
Temporal-right	.56	5.05	2.29	6.47	.427
Parietal-left	-3.58	8.69	.76	7.74	.178
Parietal-right	-2.15	6.43	.25	8.10	.381
Occipital-left	-3.23	8.87	1.76	10.16	.171
Occipital-right	-3.31	7.17	1.10	7.69	.125

Note. M = mean, SD = standard deviation

Table 7 displays that there are no significant, *p* > .5, mean difference in brain activity for men and woman in the alpha frequency. Woman have a higher average brain activity in all regions, where the greatest difference is in the left occipital lobe (ΔM = 4.99) and the smallest difference in the frontal-left lobe (ΔM = 0.56).

Discussion

The current study evaluated the relationship between SS and brain activity for different frequency bands (theta, delta and alpha). Further, the study investigated if there was a significant difference in SS scores and brain activity for the sexes. This was done to identify if brain activity could offer an objective explanation for a potential sex discrepancy of simulation sickness.

The research questions the study explores are: 1) Is there a correlation between SS and brain activity in VR? 2) Could a relationship between SS and brain activity then explain or measure the potential sex difference of SS?

The correlation analysis showed a significant negative association between total SS score and brain activity for all frequencies, except for the occipital-left in the alpha band which had a non-significant association. The t-test analyses revealed that there were no significant group differences for men and woman in SS or in brain activity.

Correlation between Simulation Sickness and brain activity

The significant relationship of total SS score and brain activity for almost all areas across all three frequencies (theta, delta and alpha) could suggest that brain activity acquired using EEG would be a good objective alternative to measure SS in VR. This finding may provide a greater level of accuracy and reliability for future measurements of SS, through one not having to rely solely on the participants subjective judgement of their experience.

A negative correlation between the variables indicates that activation in the frequency bands would be lower in a condition with a greater level of SS present. Witmer and Singer's study about presence in VR (1998) could potentially explain these results through that they found that participants experiencing a higher level of SS have a reduced presence as they are more internally focused. This could further suggest that presence of brain activity is positively associated with presence. Meaning that brain activity is reduced when experiencing SS since the participants presence would diminish.

The negative relationship between activation in the delta band and higher simulation sickness does not align with previous studies who show a positive relationship between the variables (Chang et al., 2013; Choi et al., 2009; Kim et al., 2005; Krokos and Varshney, 2022). This could be due to the setup of the study design and that activation in the delta band is seen during active sleep and affiliated with reduced attention to the physical world (Naqvi et al., 2014, White & Richards, 2009). Lower delta activity during a state of SS could suggest that participants who experience greater levels of SS require more attention to focus on the task. Participants experiencing SS tend to move less around in the environment to reduce sensorial conflict, which could require the participant to develop more strategic ways to remember the objects placement on the grid (Wienrich et al., 2022). The expectation towards the participant to perform memory tasks could also cause an alert state of mind. This could suggest that a higher level of SS is more positively correlated with beta and gamma waves which are associated with intense brain activity and problem solving.

Previous studies show varying results for the relationship for the alpha frequency and SS, where some studies support the negative association between them (Celikcan, 2019; Chang et al., 2013; Choi et al., 2009; Liu et al., 2020; Mawalid et al., 2018) and others do not (Ahn et al., 2020; Chen et al., 2010; Krokos and Varshney, 2022; Lin et al., 2007; Oh and Whangbo, 2018; Kim et al, 2019). Activation in the alpha frequency is often related to a relaxed state (Naqvi et al., 2014). Considering the physiological discomfort produced by the symptoms of SS the participants might not be in a relaxed state. This could further support that an enhanced alpha activity would not be present during a higher level of SS.

Similarly to alpha, earlier research show contradicting results where negative (Choi et al., 2009; Naqvi et al., 2015) and positive correlations (Chang et al., 2013; Heo and Yoon, 2020; Krokos and Varshney, 2022; Oh and Whangbo, 2018) have been presented for activity in the theta band and SS. The contradictory nature could possibly be explained by study design and purpose of study. Enhanced theta is often associated with accuracy and successful memory (Herweg et al., 2020). This could explain a reduced theta activation in participants experiencing a high level of SS through that they might not have completed the allocentric memory task with the same success as participants who did not experience SS. Witmer and Singer's study (1998) could further support this idea as a reduced presence caused by SS might affect allocentric performance reducing accuracy. These results could indicate that the memory performative nature of the experiment influences the association of participants theta activation and SS`s direction, through indicating that SS negatively influences accuracy in memory tasks.

The correlation analyses revealed that the strongest correlation between brain activity and SS across all frequencies was in the right parietal lobe. This could suggest that the right parietal lobe is the area that has the greatest involvement for the experience of SS. The great involvement of the right parietal lobe aligns with it being responsible and involved with perceptual tasks and spatial skills (Evans, 2023). The great focus on visual input in VR could further support the claim.

Sex difference

There present study does not demonstrate any statistical evidence for a group difference in SS between men and women for SS. This supports earlier studies from Grassini & Leumann (2020) stating that there is no significant sex difference in VR. These results would indicate that VR is not sexist through that no field of exclusion being created. Even without the sex discrepancy the future development of VR must overcome the obstacle of SS to fully employ its potential (Grassini & Leumann, 2020). Further, the results could discredit the idea that women have a tendency to over-report and men under-report as it would have been clearly reflected in the results (Rangelova et al., 2020).

One could not fully exclude Clemes and Howarth's hormone theory (2005) (hormone levels in the menstrual cycle causes higher levels of SS) through that information about the female participant's menstrual cycles was not included and could not be investigated further.

This means that oestradiol could still potentially have an effect on SS, however this would have to be researched more specifically.

That there is no sex difference between men and women for simulation sickness presented in the analysis does not exclude that one could use brain activity for examining possible sex difference for future studies. This idea could be supported through that the analysis of differences in brain activity between the sexes reflects the analysis of sex differences in SS, that there is no significant statistical differences. The findings of the correlative analysis which showed a significant relationship between the variables SS and brain activity could indicate that EEG measurements is a reliable method of measuring differences in SS for men and women.

Nonetheless the non-significant results of the analysis, it is interesting to see that the mean differences stay constant with the greatest being between the occipital-left and the smallest for the frontal-left across all frequencies. This could indicate that there is a pattern of sex difference in brain activity during simulation sickness even though the analysis did not turn out to be significant. This result would align with that the occipital left is responsible for perceptual vision which is an intrinsic part of the performed experiment and the frontal left in controlling language related movement which is absent in the experiment (Kemenoff et al., 2002; Zeng et al., 2020). The potential pattern could suggest a default in the study design, which will be further discussed under limitations below.

Limitations and future research

The present study includes some limitations, which should be adapted for future research. The goal of the study was to analyze the relationship between brain activity and SS, and if brain activity could measure or explain a sex difference for SS. Due to limited resources and time available for the processing of the EEG data the baseline measurements was not incorporated. This could reduce the accuracy and reliability of the study through that a baseline correction reduces the influence of deviations and correct the activity measured (Liland et al., 2011). This would allow one to more precisely measure the change in brain activity during a task or experiment.

The limited number of participants could also provide a limitation to the study through that there were not enough participants present to be able to measure a significant difference between men and women for SS and brain activity with a t-test. A post hoc power analysis was performed to support this claim. The analysis showed that the present study had a power of 12% when using the average effect size of the t-tests (d = 0,29). This power-value would be significantly lower than the standardized minimal power value of 80%. A priori power analysis showed that to have a power of 80% a sample of 376 participants would be necessary to find an effect.

There are also limitations for using EEG instead of positron emission topography or functional magnetic resonance imaging as it provides less specific results of the location of activity (Horwitz & Poeppel, 2002). It is difficult to know if the activity is from the cortex or from deeper brain structures. For future studies that would like to measure the location of activity more specifically or reliably should maybe opt for a different technique. For future studies continuing using EEG, it could be useful to include the beta and gamma frequency as differences in activity between the sexes.

Conclusion

The study`s aim was to explore the relationship between SS and brain activity and if this further could explain a potential sex discrepancy in VR. The study succeeded to find that there was a significant moderate to strong negative correlation between SS score and brain activity in VR, the most prominent correlation being in the right parietal cortex, a region responsible for spatial processing. However, there was no statistical significant difference between men and women for total SS score or brain activity. Future research should further explore the relationship between SS and brain activity with greater sample sizes.

References

Assenza, G. & Lazzaro, V. D. (2015). A useful electroencephalography (EEG) marker of brain plasticity: delta waves. *Neural Regeneration Research*, 10(8), 1216-1217. https://doi.org/10.4103/1673-5374.162698

Attwell, D. & Laughlin, S. B. (2001). An Energy Budget for Signaling in the Gray matter of the Brain. *Journal of Cerebral Blood Flow & Metabolism*, 21(10), 1133-1145. https://doi.org/10.1097/00004647-200110000-00001

Bromm, B. (2001). Brain Images of Pain. In M. J. Caplan (Ed.), *Physiology*. (5,16, 244-249). American Physiological Society

Buzsáki, G., Kaila, K. & Raichle, M. (2007). Inhibition and Brain Work. *Neuron*, 56(5), 771-783. https://doi.org/10.1016/j.neuron.2007.11.008

Chang, E., Kim, H. T. & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. *International Journal of Human-Computer Interaction*, 36(17), 1658-1682. https://doi.org/10.1080/10447318.2020.1778351

Chang, E., Billinghurst, M. & Yoo, B. (2023). Brain activity during cybersickness: a scoping review. *Virtual reality*. https://doi.org/10.1007/s10055-023-00795-y

Chen, Y-C., Duann, J-R., Chuang, S-W., Lin, C-L., Ko, L-W., Jung, T-P. & Lin, C-T. (2010). Spatial and temporal EEG dynamics of motion sickness. *NeuroImage*. 49, 2862-2870. https://doi.org/10.1016/j.neuroimage.2009.10.005

Clemes, S. A. & Howarth, P. A. (2005). The Menstrual Cycle and Susceptibility to Virtual Simulation Sickness. *Journal of Biological Rhythms*, 20(1), 71-82.

Duzmańska, N., Strojny, P. & Strojny, A. (2018). Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness. *Frontiers in Psychology.* https://doi.org/10.3389/fpsyg.2018.02132

Emery, W. & Camps, A. (2017). *Introduction to Satellite Remote Sensing*. Elsevier.

Evans, O. G. (2023). Parietal Lobe: Definition, Functions, Structure & Location. *Simply psychology*. https://www.simplypsychology.org/parietal-lobe.html

Grassini, S. & Leumann, K. (2020). Are Modern Head-Mounted Displays Sexist? A Systematic Review on Gender Differences in HMD-Mediated Virtual Reality. *Frontiers in Psychology*, 11(1604). https://doi.org/10.3389/fpsyg.2020.01604

Herweg, N. A., Solomon, E. A. & Kahana, M. J. (2020). Theta Oscillations in Human Memory. *Trends in Cognitive Science*, 24(3), 208-227. https://doi.org/10.1016/j.tics.2019.12.006

Horwitz, B & Poeppel, D. (2002). How can EEG/MEG and fMRI/PET data be combined. *Human Brain Mapping*, 17(1), 1-3. https://doi.org/10.1002/hbm.10057

Hu, R., Zhang, L., Meng, P., Meng, X. & Weng, M. (2022). The Neural Responses of Visual Complexity in the Oddball Paradigm: An ERP Study. *Brain Sciences*, 12(4). https://doi.org/10.3390/brainsci12040447

Jang, K-M., Kwon, M., Nam, S. G., Kim, DM. & Lim, H. K. (2022). Estimating objective (EEG) and subjective (SSQ) cybersickness in people with susceptibility to motion sickness. *Elsevier*. 102,

Jensen, L. & Konradsen, F. A. (2018). *A review of the use of virtual reality head-mounted displays in education and training* (23). Education and Information Technologies.

Kang, H. (2013). The prevention and handling of the missing data. *Korean journal of anesthesiology*, *64*(5), 402. https://doi.org/10.4097/kjae.2013.64.5.402

Kemenoff, L. A., Miller, B. L. & Kramer, J. H. (2002). Frontal Lobe. In Ramachandran, V. S. (Ed.), *Encyclopedia of the Human Brain* (pp. 317-325). Academic Press.

Keshavarz, B., Riecke, B. E., Hettinger, L. J. & Campos, J. L. (2015). Vection and visually induced motion sickness: how are they related?. *Frontiers in Psychology*, 6(472). https://doi.org/10.3389/fpsyg.2015.00472

Kim, Y. Y., Kim, H. J., Kim, E. N., Ko, H. D. & Kim, H. T. (2005). Characteristic changes in the physiological components of cybersickness. *Psychophysiology*, 42(5), 616-625. https://doi.org/10.1111/j.1469-8986.2005.00349.x

Krokos, E. & Varshney, A. (2021). Quantifying VR cybersickness using EEG. In R. D. Maacredie & D. Ballin (Ed.), *Virtual Reality* (pp. 77-89). Springer London. https://doi.org/10.1007/s10055-021-00517-2

Laessoe, U., Abrahamsen, S., Zepernick, S., Raunsbaek, A. & Stensen, C. (2023). Motion cickness and cybersickness – Sensory mismatch. *Physiology & Behaviour*, 258, 114015. https://doi.org/10.1016/j.physbeh.2022.114015

LaViola Jr., J. J. (2000). A discussion of cybersickness in virtual environments. *SIGCHI Bulletin*, 32(1), 47-56. https://doi.org/10.1145/333329.333344

Li, P., Stuart, E. A. & Allison, D. B. (2016). Multiple Imputation: A Flexible Tool for Handling Missing Data. *Journal of the American Medical Association*, 314(18), 1966-1967. https://doi.org/10.1001/jama.2015.15281

Liland, K. H., Rukke, E-O., Olsen, E. F. & Iskasson, T. (2011). Customized baseline correction. *Chemometrics and Intelligent Laboratory Systems*, 109(1), 51-56. https://doi.org/10.1016/j.chemolab.2011.07.005

Min, B-C., Chung, S-C., Min, Y-K. & Sakamoto, K. (2004). Psychophysiological evaluation of simulator sickness evoked by a graphic simulator. *Applied Ergonomics*, 35(6), 549-556. https://doi.org/10.1016/j.apergo.2004.06.002

Mishra, P., Singh, U., Pandey, C. M., Mishra, P. & Pandey, G. (2019). Application of Student's t-test, Analysis of Variance, and Covariance. *Annals of Cardiac Anaesthesia*, 22(4), 407-411. https://doi.org/10.4103/aca.ACA_94_19

Munafo, J., Diedrick, M. & Stoffregen, T. A. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. In W.

Byblow (Ed.), *Experimental Brain Research* (235, pp. 889-901). Springer Berlin Heidelberg. https://doi.org/10.1007/s00221-016-4846-7

Naqvi, S. A. A., Badruddin, N., Malik, A. S., Hazabbah, W. & Abdullah, B. (2014). EEG alpha power: An indicator of visual fatigue. *International Conference on Intelligent and Advanced Systems*

Pröbster, M. & Marsden, N. (2021). Real gender Barriers to Virtual Realities. *IEEE International Conference on Engineering*. https://doi.org/10.1109/ICE/ITMC52061.2021.9570270

Rangelova, S., Rehm, K., Diefenbach, S., Motus, D. & André, E. (2020). Gender Differences in Simulation Sickness in Static vs. Moving Platform VR Automated Driving Simulation. In Krömker, H. (Ed.) *HCI in Mobility, Transport, and Automotive Systems. Automated Driving and In-Vehicle Experience Design.* (12212). Springer, Cham. https://doi.org/10.1007/978-3-030-50523-3_11

Rubin, D. B. (1987). *Multiple imputation for nonresponse in surveys* (Vol. 81). John Wiley & Sons.

White, N. E. & Richards, L. M. (2009). Alpha-theta neurotherapy and the neurobehavioral treatment of addictions, mood disorders and trauma. *Introduction to Quantitative EEG and Neurofeedback*, 143-166. https://doi.org/10.1016/B978-0-12-374534-7.00006-X

Wienrich, C., Obremski, D. & Israel, J. H. (2022). Repeated experience or virtual nose to reduce simulator sickness? – Investigating prediction of the sensorial conflict theory and the rest-frame hypothesis in two virtual games. *Entertainment Computing*, 43 https://doi.org/10.1016/j.entcom.2022.100514

Witmer, B. G. &Singer, M. J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, 7(3), 225-240. https://doi.org/10.1162/105474698565686

Wu, B., Yu, X. & Gu, Y. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British journal of educational technology*, 51(6), 1991-2005. https://doi.org/10.1111/bjet.13023

Young, S. D., Adelstein, B. D. & Ellis, S. R. (2006). Demand Characteristics of a Questionnaire Used to Assess Motion Sickness in a Virtual Environment. *IEEE Virtual Reality Conference*. https://doi.org/10.1109/VR.2006.44

Zeng, H., Fink, G. R. & Weidner, R. (2020). Visual Size Processing in Early Visual Cortex Follows Lateral Occipital Cortex Involvement. *The Journal of Neuroscience*, 40(22), 4410-4417. https://doi.org/10.1523/JNEUROSCI.2437-19.2020

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