NeuroRegulation

A Preliminary Study Investigating the Acquisition of Valid qEEG Data While Wearing a Virtual Reality (VR) Headset

Fernando Cavallo[1], Bill Brubaker[2], Ellie Bruckner[3], and Sofia Castro[1]*

[1]Bryn Athyn College, Department of Psychology, Bryn Athyn, Pennsylvania, USA
[2]Yang Institute, Bryn Mawr, Pennsylvania, USA
[3]Widener University, Institute for Graduate Clinical Psychology, Chester, Pennsylvania, USA

Abstract

The use of virtual reality (VR) therapy is being utilized and promoted for a wide range of treatment applications. Yet, the majority of clinical evidence that supports the efficacy of VR treatment has been established utilizing reports of subjective outcome variables, such as rating scales or a reduction of symptoms reported by the patient. Instead, the present study supports the use of quantitative electroencephalography (qEEG) as a more precise and objective method for assessing treatment efficacy involving the use of VR-based treatments. Although a few studies have attempted to establish physiological evidence from qEEG recordings to strengthen the efficacy of pre-post treatment effects for VR-based treatments, these attempts have been based upon very small sample sizes or case studies. Therefore, to the best of our knowledge, prior studies have failed to uniformly account for ingenuine treatment effects that could arise from merely wearing a VR headset while acquiring qEEG. The current preliminary study sought to systematically measure any potential confounding effects that wearing a VR headset could produce by measuring and comparing the baseline qEEG recordings for the eyes-open, resting condition (staring at a dot) with and without the VR headset for 28 participants. The present results revealed very minimal significant differences between the two conditions when analyzed collectively and no significant differences for the male participants. The implications of these findings are discussed and provide preliminary support for confidently reporting qEEG efficacy data involving the use of a VR headset. Additionally, the current study is believed to have successfully established a valid and standardized approach for reliably obtaining active or real-time qEEG data while wearing a VR headset in order to confidently report the physiological effects of VR immersion on electrical brain activity.

Keywords: qEEG; virtual reality; VR therapy.

Citation: Cavallo, F., Brubaker, B., Bruckner, E., & Castro, S. (2023). A preliminary study investigating the acquisition of valid qEEG data while wearing a virtual reality (VR) headset. *NeuroRegulation, 10*(3), 170–178. https://doi.org/10.15540/nr.10.3.170

***Address correspondence to**: Dr. Fernando Cavallo, Bryn Athyn College, Department of Psychology, 2945 College Drive, Bryn Athyn, PA 19009, USA. Email: fernando.cavallo@brynathyn.edu

Edited by:
Rex L. Cannon, PhD, Currents, Knoxville, Tennessee, USA

Reviewed by:
Rex L. Cannon, PhD, Currents, Knoxville, Tennessee, USA
Randall Lyle, PhD, Mount Mercy University, Cedar Rapids, Iowa, USA

Introduction

As virtual reality (VR) devices have grown in availability and use, so too has the body of literature on the effects and possible implications that VR can have. Current research efforts have explored VR's effectiveness in education, the treatment of mental health conditions, pain relief, training of practical skills, developing procedural knowledge, improving athletes' understanding of and intention to report concussions, enhancing conceptual knowledge, and enhancing meditation and presence (Baceviciute et al., 2021; Daneshvar et al., 2021; Hufnal et al., 2021; Tran et al., 2022). With the increase in this research, the methods for evaluating effectiveness and impact have also advanced. More studies on VR are beginning to employ quantitative electroencephalography (qEEG) data to further analyze cognitive impacts of the VR platform (Baceiviciute et al., 2021; Tarrant et al., 2018; Tremmel et al., 2019). Employing qEEG measurement allows researchers to move away from subjective questionnaires rating the individual's experience in VR, and instead allows for more objective and continuous data that is collected in real time during the exposure (Hertweck et al., 2019).

While the application of qEEG measurements in studying the impact of VR has increased, there is currently a lack of understanding of the potential impacts VR devices may have on qEEG data acquisition. Of recent studies that have either analyzed qEEG data during VR experiences (Tarrant et al., 2018; Tremmel et al., 2019) or compared qEEG data for 2-D versus VR videos (Xu & Sui, 2021), few have established validity for acquiring accurate qEEG data while wearing a VR headset. That is, thus far this new and growing body of research has yet to assure the scientific community whether certain factors present during qEEG acquisition (i.e., the weight of the headset, interference with electrode signal detection, artifact produced by physical movements during interactive VR experience) interfere with the reliability and validity of VR-based qEEG data.

While understanding of the validity of qEEG in VR technology is limited, current research has established some understanding of the interaction of qEEG and VR. One study investigating the potential impacts of electrical signals from the VR device did not find any significant impacts on qEEG readings (Cattan et al., 2018). While this study helps to provide evidence that the impact of the VR headset alone may not impede qEEG readings, the study used a more primitive VR device (one using smartphones), that is not representative or fully generalizable to the current state of advanced VR technology. A second study investigated qEEG signal quality obtained while using two popular VR head-mounted displays. Results revealed qEEG data being fairly consistent across experimental groups which consisted of eyes-open and eyes-closed trials with VR headsets and without (Hertweck et al., 2019). While this study suggested the viability of qEEG acquisition, it did not compare traditional brain-mapping procedures to ensure validity and suggested further analysis of conditions is needed for the field (Hertweck et al., 2019). Hence, there remains a gap in the literature and the research field on the validity of acquiring qEEG data with recent VR technology. Over the past several years the application of VR for mental health treatment has increased and is also supported by the American Psychiatric Association (APA, 2021). VR therapy is being promoted nationally and internationally by companies such as Amelia Virtual Care (Gurr & Laitz, 2023) based upon clinical case studies that rely upon subjective outcome variables. Another company, EaseVRx, recently received FDA approval for the marketing and use of VR therapy for patients 18 years or older diagnosed with chronic lower back pain (FDA, 2021).

The present study seeks to fill the gaps in our understanding of the reliability and validity of qEEG data collection with VR technology and adds several novel contributions to the field. The current study expands upon previous studies that have suggested qEEG data is viable with VR (Cattan et al., 2018; Hertweck et al., 2019) by collecting data under longer intervals using an eyes-open baseline condition in VR. An analysis of brain mapping is also utilized to compare eyes-open baseline with and without VR. Previous studies that have acquired baseline data have done so using immersive 3D experience compared to 2D screen applications using the same virtual environment (Tran et al., 2022). This study, however, will be one of the first to add an understanding of whether or not the VR headset itself (in this experiment, the Meta Quest 2, formerly called the Oculus) causes any difference in qEEG data by comparing a task in VR with a natural environmental condition. Additionally, many previous studies of qEEG and VR have been completed with small sample groups or as case studies, while the present study was able to recruit a larger sample size. Given previous research, we hypothesize that there should not be a significant difference when comparing the baseline data collected with and without the VR headset.

Materials and Methods

Participants

The study consisted of 30 participants ranging from 19–72 years of age (57% male, 43% female). No demographic data, other than gender and age, was obtained from the participants. This study was conducted in an empty classroom located in the college. The study was approved by the Bryn Athyn Institutional Review Board (Bryn Athyn College, PA). Participants were recruited through posted advertisements using digital or paper flyers posted throughout the college campus and community. Additionally, students enrolled in introductory psychology courses at the college were offered extra credit in their course for participating in the study.

Equipment

Virtual Reality (VR) Headset. The experiment was conducted using the Meta Quest 2 (formerly the Oculus) VR headset. The headset comes equipped with two handheld controllers. The Meta Quest 2 is typically used for gaming and watching 360-degree VR videos with 20 pixels per degree visuals and a

Fast-Switch LCD display spanning 1832 x 1920 pixels per eye with a 120 Hz refresh rate. The headset weighs 503 grams and measures 224 x 450 mm.

Electro-Cap. qEEG data was obtained utilizing a standard Electro-Cap 19-channel EEG with ear lead attachments (Bio-Medical Instruments, Clinton Township, MI). They are made of an elastic spandex-type fabric with recessed, pure tin electrodes attached to the fabric. The electrodes on the standard caps are positioned to the International 10–20 method of electrode placement. The sizes utilized for the current experiment ranged from 52–56 cm (medium) to 58–62 cm (large) depending upon the size of the participants' head circumference.

Measures

EEG Data Collection. The EEG data in this study was obtained using a Discovery 24 Series amplifier (BrainMaster Technologies, Bedford, OH). The Discovery 24 offers 1024 samples per second on 22 channels, with 24-bit resolution, and an amplifier bandwidth from DC (0.000 Hz) to 80 Hz. The EEG data in this study was sampled with 19 electrodes in the standard 10–20 International placement using a standard electrode cap plus two additional channels used for separate references attached to the right and left ears. Automatic artifacting was conducted using qEEG-Pro (qEEG Pro B.V., Verdunplein, The Netherlands) software's Standardized Artifact Rejection Algorithm (S.A.R.A). The files were then converted to enable NeuroStat and NeuroBatch (Applied Neuroscience, Inc., St. Petersburg, FL) to generate group mean statistics and paired-group *t*-test analyses.

Procedures

Upon replying to the digital or paper recruitment flyers, participants scanned the QR code contained on the flyer in order to select an available 60-min time slot. Participants received an email 1 to 2 days prior to their scheduled appointment which explained what to expect during their appointment as well as standard instructions for the proper clinical preparation for having a qEEG conducted (i.e., not using product other than basic shampoo when washing their hair prior to the appointment).

Upon their arrival on the day of their scheduled appointment, all participants read a written description of the study process contained in the IRB consent form requiring their signed consent. Once their consent was obtained, participants were asked to sit in a comfortable chair facing a whiteboard situated 5 feet from the chair. The study sessions took place in a secluded classroom away from noise and visual distractions. The participants were informed that the procedure for placing the Electro-Cap on their head and establishing "clean recordings" would take approximately 20–25 min followed by two conditions lasting approximately 6 min each. All participants were asked to turn off their phones and leave them with their personal items in a chair located in the back of the room to prevent distraction.

The participants then were prepared for the active qEEG recording by ensuring the Electro-Cap was securely fitted on their head adhering to standard qEEG acquisition protocol involving the application of Electro-Gel and Nuprep skin prepping gel to ensure low electrode impedance. In general, impedance levels up to 10 Ω are acceptable involving the use of qEEG recordings in clinical and research applications. The current researchers obtained impedance levels less than 5 Ω for the majority of the participants in each of the 19 locations on the scalp and less than 10 Ω impedance for all participants. Once the participant's qEEG reading was deemed to be suitable for valid data acquisition and recording, each participant was briefly taught how to minimize eye blinking and muscle artifact, such as jaw or shoulder tension. Participants were provided with real-time visual feedback from a laptop screen to demonstrate how eye blinking and muscle artifact affect the qEEG data acquisition, along with suggestions of how to minimize these artifacts during the recording (i.e., take a deep breath and then exhale, take a long and slow blink when necessary).

Following these steps, the participant was then instructed to stare at a black dot that was placed on a whiteboard located at eye level at a 5-foot distance for 6 min (Condition 1: eyes open). Upon completion of the first condition, the participant was provided with a 2- to 3-min break to relax while remaining in the chair and still wearing the Electro-Cap. During the brief break, the experimenter powered up and synched the Meta Quest 2 VR headset for the second condition (Condition 2: eyes open with VR headset). Then, the VR headset was placed directly upon the Electro-Cap (see Figure 1) and impedance readings were again measured to ensure that all 19 scalp locations maintained an impedance less than 10 Ω.

Figure 1. *VR Headset Placement for qEEG Recording*.

Once again, the current researchers obtained impedance levels less than 5 Ω for the majority of the participants and less than 10 Ω impedance for all participants. Once the VR headset was properly secured, the participants were asked to stare at a black dot that appeared in the VR headset, which was a still image of the black dot that they were asked to stare at on the whiteboard during the first condition. The black dot was placed at eye level by the experimenter using a synched iPad or iPhone with verbal feedback provided by the participant to confirm that the black dot, based upon the participant's visual perception, was at eye level and the same distance from view as experienced during the first condition. Once confirmation of the dot placement was confirmed, the participant was again asked to stare at the dot for 6 min. Following the completion of the study, all participants were provided with paper towels and provided a washroom where they could remove some of the excess Electro-Gel from their hair before leaving.

Data Analysis

qEEG is produced through statistical analysis of the EEG; that is, conversion of the time domain EEG record (voltage plotted against time) to the frequency domain (amplitude or power plotted against frequency) using the fast Fourier transformation (FFT). The qEEG bands we considered were delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz). In this study, raw EEG data were collected noninvasively from the participant's scalp during the two experimental conditions using a BrainMaster Discovery 20-channel EEG (BrainMaster Technologies, Bedford, OH). Electrode caps were used to place recording electrodes over the 19 standard regions defined by the International 10/20 system referenced to linked ears: Fp1, Fp2, F3, F4, F7, F8, T3, T4, C3, C4, P3, P4, T5, T6, O1, O2, Fz, Cz, and Pz. All channels of EEG were acquired with 24-bit resolution at the sampling rate of 256 Hz.

The EEG was recorded for 6 min for each of the two conditions. Automated artifacting using SARA was uniformly applied without exception in order to remove human error or bias in the analysis and selection of which data should be rejected. The NeuroGuide EEG and qEEG analysis system software (Applied Neuroscience, Inc., Largo, FL) was used for the signal processing of the qEEG. Quantitative data were presented using absolute power group means comparison between the two experimental conditions utilizing a within-subjects design for the following four EEG frequency bandwidths: delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz). Quantitative data analysis was also performed utilizing NeuroStat's paired-group *t*-test for comparing the absolute power differences between the two experimental conditions across the 19 scalp locations acquired for each of the four aforementioned frequency bandwidths.

Automated artifacting using S.A.R.A. was uniformly applied without exception in order to remove human error or bias in the analysis and selection of which data should be rejected. Finally, the Bonferroni correction was applied to adjust for the number of paired-group *t*-tests conducted for each set of analyses to properly adjust the critical *p*-value for determining levels of significance.

Results

There were 30 participants recruited (17 males, 13 females). The age range was 19–72 years old (M = 39.3) years old. Out of these 30 participants, 2 females were eliminated from the study due to the presence of excess noisy channels. According to the qEEG-Pro manual, noisy channels are defined as channels that contain a disproportional amount of high-frequency power due to muscle artifacts, and the manual recommends that an individual's qEEG data be rejected when five or more noisy channels are present. The final sample included 28 participants consisting of 61% male and 39% female participants.

Group Means Analysis

Eyes-Open Resting Without VR Headset. Group means were recorded for this condition. This condition revealed absolute power measures with high activity levels in delta (1–4 Hz) and theta (4–8 Hz) in the central region of the brain. High activity levels were detected in alpha (8–12 Hz) and in beta (12–25 Hz) in the occipital region of the brain (see Figure 2).

Eyes-Open Resting With VR Headset. Similar patterns of activity were detected in the eyes-open condition with the Meta Quest 2 headset. Absolute power measures revealed high activity levels in delta (1–4 Hz) and theta (4–8 Hz) in the central region of the brain. High activity levels were detected in alpha (8–12Hz) and in beta (12–25 Hz) in the occipital region of the brain. High activity was also detected in beta (12–25 Hz) in the frontal region of the brain (see Figure 3).

Paired-Group *t*-test

Eyes-Open Resting Without VR Headset vs. Eyes-Open Resting With VR Headset. To compare the differences between the two conditions a paired-group *t*-test was performed using data from the 28 subjects (see Figure 4). However, the topographic maps in Figure 3 do not represent the significant *p*-value levels after the Bonferroni correction was applied as the NeuroStat software applications allow the user to manually adjust the *p*-values. Instead, the current researchers divided the critical *p*-value (p = .05) by the number of comparisons (N = 28) to determine the adjusted critical *p*-value ($p < .002$). Therefore, only regions depicted in dark red in Figure 4 below indicate possible significant difference since the dark red represents *p*-values ranging from 0.00 to 0.005.

Figure 2. *Eyes-Open Resting Without VR Headset.*

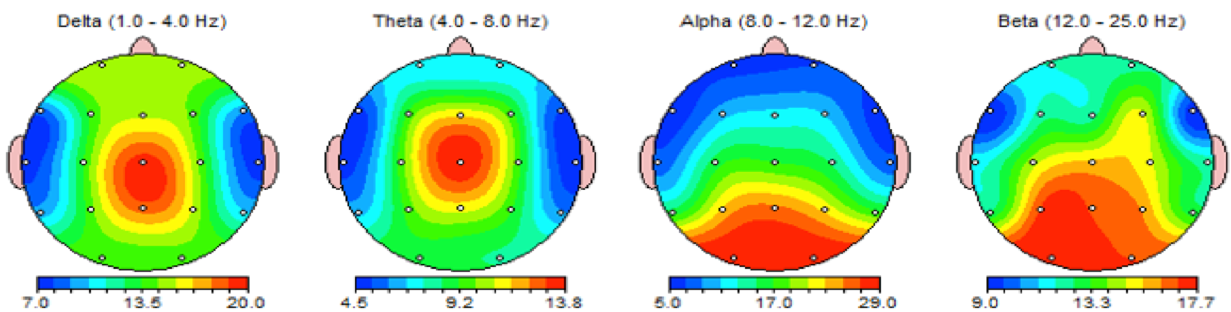


Figure 3. *Eyes-Open Resting With VR Headset.*

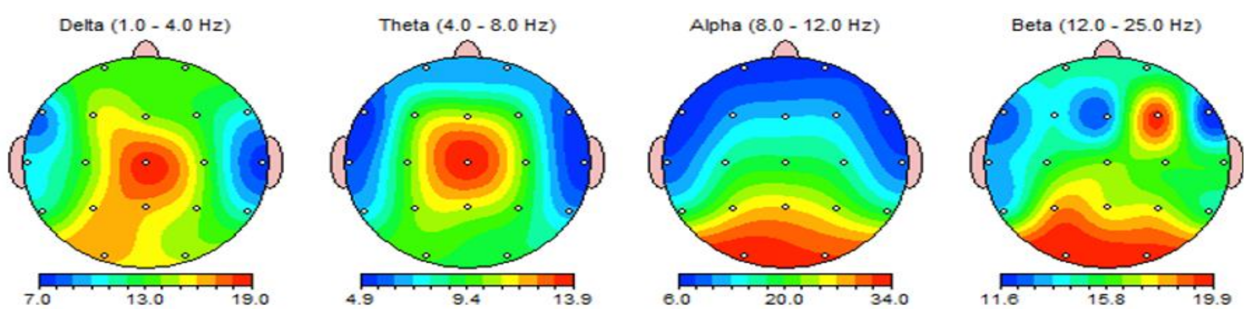
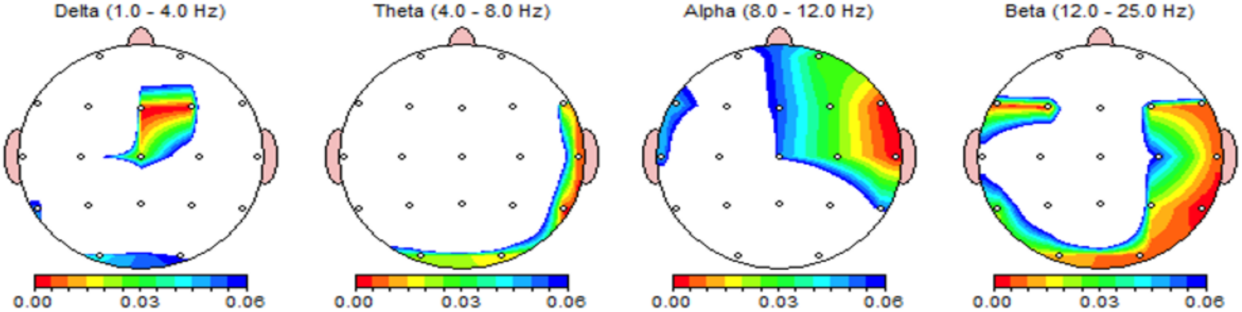


Figure 4. *Paired-Group t-test. FFT Absolute Power (uV Sq).*



After applying the Bonferroni correction to the NeuroStat automated paired *t*-test report, the results were analyzed and significant findings for the adjusted *p*-values were more specifically identified and highlighted according to the 19 electrode locations in the standard 10–20 International placement (see Tables 1 and 2).

The paired-group analysis revealed significant differences in the right hemisphere absolute power of delta (1–4 Hz) in the frontal regions ($p < .002$; see Table 1). Furthermore, significant differences were found in alpha (8–12 Hz) and beta (12–25 Hz), in the temporal regions of the brain. In the fronto-central of the brain, significant differences were found in delta (1–4 Hz), mainly in the frontal region of the brain ($p < .002$; see Table 1). No significant differences were found in the left hemisphere (see Table 1).

Table 1

Paired-Group t-test for Eyes Open With vs. Without VR Headset.

FFT Absolute Power Group Mean (uV Sq)
Post hoc Bonferonni Paired *t*-test Correction ($N = 28$, $p < .002$)*

	Intrahemispheric: LEFT			
	Delta	Theta	Alpha	Beta
Fp1 – LE	0.144	0.611	0.074	0.291
F3 – LE	0.995	0.708	0.084	0.002
C3 – LE	0.070	0.590	0.204	0.179
P3 – LE	0.703	0.253	0.251	0.118
01 – LE	0.042	0.025	0.192	0.013
F7 – LE	0.554	0.318	0.045	0.005
T3 – LE	0.117	0.116	0.046	0.077
T5 – LE	0.051	0.141	0.127	0.026

Table 1

Paired-Group t-test for Eyes Open With vs. Without VR Headset.

FFT Absolute Power Group Mean (uV Sq)
Post hoc Bonferonni Paired *t*-test Correction ($N = 28$, $p < .002$)*

	Intrahemispheric: RIGHT			
	Delta	Theta	Alpha	Beta
Fp2 – LE	0.126	0.646	0.028	0.377
F4 – LE	0.000*	0.444	0.030	0.012
C4 – LE	0.097	0.274	0.026	0.056
P4 – LE	0.253	0.207	0.120	0.019
02 – LE	0.061	0.016	0.202	0.006
F8 – LE	0.426	0.012	0.003	0.006
T4 – LE	0.402	0.006	0.001*	0.007
T6 – LE	0.159	0.003	0.051	0.000*
	Intrahemispheric: CENTER			
	Delta	Theta	Alpha	Beta
Fz – LE	0.000*	0.374	0.054	0.253
Cz – LE	0.019	0.834	0.051	0.102
Pz – LE	0.172	0.770	0.226	0.365

Gender Effect

To investigate whether there were any differences between males and females in the two conditions a paired *t*-test was performed. Bonferroni *p* values were adjusted for males ($p < .0027$) and females ($p < .005$) due to smaller sample size. For males, there were no significant differences between the two conditions (eyes open with or without VR headset) in the absolute power of delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz; see Table 2).

Table 2
Paired-Group t-test for Eyes Open With vs. Without VR Headset (Male Participants).

FFT Absolute Power Group Mean (uV Sq)
Post hoc Bonferonni Paired *t*-test Correction (*N* = 17, *p* < .0029)*

	Intrahemispheric: LEFT			
	Delta	Theta	Alpha	Beta
Fp1 – LE	0.646	0.992	0.248	0.668
F3 – LE	0.234	0.283	0.507	0.048
C3 – LE	0.560	0.853	0.848	0.489
P3 – LE	0.415	0.562	0.647	0.568
01 – LE	0.023	0.163	0.446	0.130
F7 – LE	0.856	0.895	0.369	0.013
T3 – LE	0.170	0.634	0.435	0.084
T5 – LE	0.094	0.487	0.478	0.315
	Intrahemispheric: RIGHT			
	Delta	Theta	Alpha	Beta
Fp2 – LE	0.611	0.981	0.155	0.922
F4 – LE	0.041	0.376	0.223	0.168
C4 – LE	0.368	0.725	0.223	0.253
P4 – LE	0.887	0.368	0.382	0.382
02 – LE	0.029	0.130	0.486	0.486
F8 – LE	0.506	0.071	0.048	0.048
T4 – LE	0.126	0.049	0.032	0.032
T6 – LE	0.042	0.037	0.199	0.199
	Intrahemispheric: CENTER			
	Delta	Theta	Alpha	Beta
Fz – LE	0.025	0.240	0.327	0.630
Cz – LE	0.317	0.806	0.302	0.306
Pz – LE	0.708	0.998	0.590	0.980

Table 3
Paired-Group t-test for Eyes Open With vs. Without VR Headset (Female Participants).

FFT Absolute Power Group Mean (uV Sq)
Post hoc Bonferonni Paired *t*-test Correction (*N* = 11, *p* < .005)*

	Intrahemispheric: LEFT			
	Delta	Theta	Alpha	Beta
Fp1 – LE	0.042	0.170	0.388	0.375
F3 – LE	0.525	0.343	0.098	0.027
C3 – LE	0.095	0.470	0.050	0.016
P3 – LE	0.297	0.373	0.169	0.104
01 – LE	0.783	0.153	0.134	0.061
F7 – LE	0.250	0.178	0.046	0.106
T3 – LE	0.476	0.118	0.019	0.261
T5 – LE	0.193	0.144	0.047	0.021
	Intrahemispheric: RIGHT			
	Delta	Theta	Alpha	Beta
Fp2 – LE	0.052	0.176	0.207	0.348
F4 – LE	0.002*	0.937	0.062	0.039
C4 – LE	0.391	0.211	0.061	0.043
P4 – LE	0.252	0.594	0.177	0.042
02 – LE	0.798	0.231	0.221	0.048
F8 – LE	0.546	0.218	0.060	0.015
T4 – LE	0.249	0.201	0.031	0.009
T6 – LE	0.541	0.106	0.132	0.034
	Intrahemispheric: CENTER			
	Delta	Theta	Alpha	Beta
Fz – LE	0.004*	0.821	0.085	0.184
Cz – LE	0.047	0.799	0.054	0.194
Pz – LE	0.237	0.958	0.215	0.154

For females, there were significant differences in the right and central hemispheres. In the right hemisphere, there was a significant difference in the absolute power of delta (1–4 Hz) in the frontal region ($p < .005$; see Table 3). There was also a significant difference in the absolute power of delta (1–4 Hz), in the fronto-central region ($p < .005$; see Table 3). No significant differences were found in the left hemisphere (see Table 3).

Discussion

To our knowledge, this is the first study to systematically consider and examine the validity and reliability of qEEG data acquisition involving a VR interface beyond a single or small sample size research design. Specifically, the current study was designed to provide researchers, mental health clinicians, and neurofeedback therapists implementing VR-based therapy a standardized and valid approach to scientifically examining the effects of such therapy modalities. The current research was designed to investigate two primary objectives: a) determine whether simply wearing a VR headset during the eyes-open resting qEEG recording significantly alters baseline levels of electrical brainwave patterns, and b) establish a standardized method for properly securing the VR headset on top of the Electro-Cap when performing qEEG data acquisition to secure valid recordings.

To address the first objective, the findings of the present study revealed some minimal differences in brainwave patterns during the resting eyes-open condition with the VR headset when compared to the standard eyes-open resting baseline condition employed by qEEG clinicians. A comparison of the absolute power differences in regional brainwave activity across frequency bands for both conditions provided the ability to determine directionality for the significant differences indicated by the paired-group *t*-test. The significant decrease in delta activation suggests an activation of the anterior cingulate corresponding to an increase in focus and attention. Increased beta activation in the right occipito-temporal area suggests an increase in visual sensation activation and processing. Furthermore, increased alpha activation in the right hemisphere suggests a suppression of avoidance related to a sense of being comfortable and unafraid. Therefore, it would appear that when participants were asked to establish a resting, eyes-open baseline qEEG by staring at a dot placed inside the VR headset, the research design resulted in a group effect suggesting a greater orientation response in the brain associated with an increase in visual attention while being in a safe environment.

While these findings suggest some measurable effect on the resting qEEG while wearing the VR headset, the majority of the location-specific bandwidth power values were not significantly different than the comparison eyes-open, resting baseline condition without the VR headset. These findings would generally support prior and future research studies which measure VR efficacy without the need to conduct a separate baseline qEEG recording with the VR headset, particularly when attention is given to the few location-specific changes (right: F4 delta, T4 alpha, T6 beta, and central: Fz delta). Additionally, the few significant changes observed in the current study could arguably be considered part of the cumulative VR effect that cannot and possibly should not be excluded or controlled. However, future replication group studies are warranted to provide further assurance to the qEEG community of these findings.

Also, there were some noteworthy limitations to our design and data analysis. First, the current research design did not counterbalance the two conditions. Instead, all participants' resting, eyes-open qEEG was measured first without the headset for 6 min followed by the resting, eyes-open qEEG with the VR headset. This may have caused an order effect and should be considered in future research. Secondly, the current data analysis was conducted according to traditional methodologies employed in qEEG comparison studies for treatment efficacy or group comparison. That is, employing the Bonferroni correction as the most conservative measure for protecting against Type 1 errors to minimize the chances of falsely indicating valid significant results or efficacy of the intervention (i.e., efficacy of neurofeedback intervention). However, the current study did not guard equally against Type 2 errors or failure to reject a null hypothesis. Therefore, future replication studies may wish to include such corrections or consistently apply the Bonferroni correction whenever attempting to claim a significant treatment effect, especially for VR-based interventions.

Additional analysis of a possible gender effect was significant in the current study, indicating that females showed significant delta activation in the right and central hemisphere, but males did not show any significant differences in any of the location-specific qEEG bandwidth power values across both conditions. Additionally, unsolicited anecdotal statements made by participants after removing the VR headset may be of qualitative interest for future studies to measure. For example, some participants noted feeling calmer and more relaxed while wearing the headset and, on the contrary, others indicated feeling more tense in the VR headset condition. Some participants expressed their familiarity with using a VR headset, while others indicated it was their first time wearing a VR headset. It is also noteworthy to mention that anecdotal evidence suggested that far more males were more familiar and experienced with the VR headset than females, which could have contributed to the gender effect. Therefore, future studies may wish to systematically investigate participants' subjective experience while wearing the VR headset and account for prior VR experience as a potential contributing factor.

In regard to the second objective, we believe this to be one of the first studies to have systematically designed a standardized approach for recording qEEG for group research designs involving a VR headset. Specifically, we developed a framework for assuring consistent placement of the VR headset bands on top of the Electro-Cap sensors at Fz, Cz, Pz, T7, P7,01, T8, P7, and 02 (see Figure 1) and the actual headset resting on Fp1 and Fp2 (see Figure 1). The acquisition of valid and reliable qEEG recordings was established by measuring and assuring the impedance levels were below 10 Ω for each electrode sensor, both before and after placing the VR headset on participants. Also, rather than having participants stare at a blank wall with a dot through a grainy passthrough (see-through) option provided by the VR headset, the present study utilized a still picture of the same dot and wall inside the VR headset to control as much as possible for differences in visual stimuli across the two conditions. Finally, the qEEG data were processed using an automated artifact rejection procedure (S.A.R.A) to eliminate any potential experimenter bias or error that hand-artifacting methods could present. Therefore, we believe the current study will help provide an essential framework for future researchers wishing to replicate and further validate the present research findings as well as acquire real-time qEEG data to determine the efficacy of VR-based interventions.

Although the results of this study provided preliminary evidence suggesting that it is not necessary to obtain a separate resting qEEG baseline measure while wearing the VR headset, future replication studies are required that address the limitations of the current study and continue to systematically adapt and adjust methodological qEEG acquisition procedures for real-time qEEG recordings for VR-based interventions as the VR technology advances and changes. For example, the latest version of the Meta Quest VR headset (Meta Quest Pro) released in October 2022 has the battery pack situated on the only securing headset strap located and resting on the back of the head.

Author Disclosure

Authors have no grants, financial interests, or conflicts to disclose.

References

American Psychiatric Association. (2021, June 21). *Expanding mental health users for virtual reality*. https://www.psychiatry.org/News-room/APA-Blogs /Expanding-Mental-Health-Uses-for-Virtual-Reality

Baceviciute, S., Terkildsen, T., & Makransky, G. (2021). Remediating learning from non-immersive to immersive media: Using EEG to investigate the effects of environmental embeddedness on reading in virtual reality. *Computers & Education, 164*, 104122. https://doi.org/10.1016 /j.compedu.2020.104122

Cattan, G., Andreev, A., Mendoza, C., & Congedo, M. (2018). The impact of passive head-mounted virtual reality devices on the quality of EEG signals. *2018 VRIPHYS Workshop on Virtual Reality Interaction and Physical Simulation.* https://doi.org/10.2312/vriphys.20181064

Daneshvar, D. H., Yutsis, M., Baugh, C. M., Pea, R. D., Goldman, S., Grant, G. A., Ghajar, J., Sanders, L. M., Chen, C. L., Tenekedjieva, L.-T., Gurrapu, S., Zafonte, R., & Sorcar, P. (2021). Evaluating the effect of concussion-education programs on intent to report concussion in high school football. *Journal of Athletic Training*, *56*(11), 1197–1208. https://doi.org/10.4085/509-20

Food and Drug Administration (FDA). (2021, November 16). *FDA authorizes marketing of virtual reality system for chronic pain reduction*. https://www.fda.gov/news-events/press-announcements/fda-authorizes-marketing-virtual-reality-system-chronic-pain-reduction

Gurr, H. & Laitz, E.K. (2023). *Clinical evidence of virtual reality in mental health treatment* [Webinar]. [Online]. Amelia Virtual Care sponsored by American Psychiatric Association, April 21, 2023

Hertweck, S., Weber, D., Alwanni, H., Unruh, F., Fischbach, M., Latoschik, M. E., & Ball, T. (2019). Brain activity in virtual reality: Assessing signal quality of high-resolution EEG while using head-mounted displays. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR),* Osaka, Japan (pp. 970-971). https://doi.org/10.1109/VR.2019.8798369

Hufnal, D., Johnson, T., Yilderim, C., & Schofield, D. (2021). Impact of VR and desktop gaming on electroencephalogram (EEG) ratings. *2021 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, Kuala Lumpur, Malaysia. https://doi.org/10.1109 /icecce52056.2021.9514188

Tarrant, J., Viczko, J., & Cope, H. (2018). Virtual reality for anxiety reduction demonstrated by quantitative EEG: A pilot study. *Frontiers in Psychology*, *9*, Article 1280. https://doi.org /10.3389/fpsyg.2018.01280

Tran, Y., Austin, P., Lo, C., Craig, A., Middleton, J. W., Wrigley, P. J., & Siddall, P. (2022). An exploratory EEG analysis on the effects of virtual reality in people with neuropathic pain following spinal cord injury. *Sensors*, *22*(7), 2629. https://doi.org/10.3390/s22072629

Tremmel, C., Herff, C., Sato, T., Rechowicz, K., Yamani, Y., & Krusienski, D. J. (2019). Estimating cognitive workload in an interactive virtual reality environment using EEG. *Frontiers in Human Neuroscience*, *13*, Article 401. https://doi.org/10.3389 /fnhum.2019.00401

Xu, X., & Sui, L. (2021). EEG cortical activities and networks altered by watching 2D/3D virtual reality videos. *Journal of Psychophysiology*, *36*(1), 4–12. https://doi.org/10.1027/0269-8803/a000278

Received: June 8, 2023
Accepted: July 25, 2023
Published: September 30, 2023