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ORIGINAL ARTICLE

# Single-channel EEG measurement of engagement in virtual rehabilitation: a validation study

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**Abstract**
Stroke rehabilitation suffers from low levels of patient engagement, impeding recovery. Virtual rehabilitation (VR) approaches can improve patient outcomes; however, there is limited understanding of the participant's user experience and the field lacks a validated, objective measure of VR engagement. A neurophysiological measure of engagement in healthy adults was therefore examined, to inform future clinical studies. Twenty-four participants ($M_{age}$ 26.7 years, range 18–47) interacted with a tabletop VR system (*Elements* DNA, or EDNA), after which they rated their experience on the presence questionnaire (PQ). Separately, participants completed tasks eliciting low (*resting* eyes-open and -closed) and high (EDNA VR and roller coaster *simulation*) levels of engagement while continuous electroencephalogram (EEG) was recorded from a single, left pre-frontal electrode. EEG differences between the *resting* and *simulation* conditions included an increase in theta power ($p < 0.01$) and a decrease in alpha power ($p < 0.01$). Importantly, theta power in *simulation* conditions correlated with PQ scores expressing the hands-on EDNA VR experience ($r_s = 0.38$–$0.48$). In conclusion, the current results provide proof of concept that increased frontal theta power in healthy adults provides a valid measure of user engagement in VR simulation and participation. As the practical potential of VR is increasingly realised in stroke rehabilitation, objective EEG-based measures of engagement may provide a convenient and sensitive technique to assist in evaluating these interventions.

**Keywords** Engagement · Presence · Electroencephalogram · Rehabilitation · Virtual reality

## 1 Introduction

In the context of health interventions, *engagement* refers to mental states, experiences, and processes that foster deliberate and effortful patient commitment to working towards their healthcare goals (Barello et al. 2012; Bright et al. 2015). Following the neuro-trauma of stroke, patient engagement is critical to the process of rehabilitation and predictive of positive outcomes (Burke et al. 2009a; Langhorne et al. 2011; Maclean et al. 2000). A combination of internal (e.g. depressive moods, fear of pain, or negative attitudes; Lequerica et al. 2009), environmental (e.g. poor client-therapist relationship, unclear session goals; Lequerica and Kortte 2010) or task-related issues (e.g. excessive task difficulty and insufficient affordances for action; Triberti and Riva 2015) can diminish patient engagement. Procedural barriers, such as repetitive and mundane exercises (Maclean et al. 2000), are also frequently cited as contributing to low levels of patient engagement with conventional rehabilitation techniques (Bright et al. 2015; Lenze et al. 2004; Lequerica et al. 2009).

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Virtual reality approaches have been developed to increase motivation to participate in rehabilitation by presenting exercises in an enjoyable, interactive, and novel manner (Duckworth 2015; Howard 2017; Mumford et al. 2012; Rogers et al. 2019). Based on virtual reality simulation and interactive technologies, and informed by neuroscience and learning theory, these so-called virtual rehabilitation (VR) approaches attempt to maximise user engagement by the provision of: (1) an *enriched therapeutic environment* (Perez et al. 2004) that both affords action and engages the patient's cognitive attention; (2) *augmented feedback* in real time and after performance (Maier et al. 2019; Zimmerli et al. 2013) to enhance motor learning and future movement planning; and (3) in-system scaling of the level of task challenge (Schultheis and Rizzo 2001), ensuring *dynamic scaffolding* of the user's processing and response capabilities.

Meta-analyses of post-stroke VR interventions have repeatedly revealed the approach is more beneficial for recovery than conventional therapies (Aminov et al. 2018; Laver et al. 2017; Lohse et al. 2014; Palma et al. 2017). More specifically, recent reviews have identified that virtual reality approaches provide a medium to enhance both motor (i.e. via provisions for variable practice, augmented feedback, and high intensity training) and social cognitive learning (e.g. vicarious learning, motor simulation, and performance accomplishment using tasks that are finely scaled in difficulty) in stroke rehabilitation (Imam and Jarus 2014; Maier et al. 2019). However, despite an evidence-based approach to the development of VR, and much deliberation about the active ingredients of VR that may contribute to engagement (Burke et al. 2009b; Levin 2011; Lewis and Rosie 2012; Zimmerli et al. 2013), there is little work formally evaluating whether VR approaches can, in fact, enhance patient engagement. Engagement is often assessed via self-report measures of the subjective experience of *presence* (Barello et al. 2012; Kober et al. 2012). Presence refers to the subjective experiences mediated by an environment, including the extent to which it engages our senses, captures our attention, and fosters our active involvement (Witmer et al. 2005).

Self-report approaches require attention, comprehension, self-reflection, and communication skills that are often compromised after stroke and other neurological injuries. Alternatively, electrophysiological methods can provide an objective measure of a user's immediate responses to VR, which correlate with traditional self-report measures of engagement (Leiker et al. 2016; Zimmerli et al. 2013). In particular, the electroencephalogram (EEG), by means of scalp electrodes, can provide real-time information on underlying brain electrical activity, with the level of task engagement reliably associated with EEG indices of attentional allocation, visual interpretation, and information processing (Berka et al. 2007). Specifically, increased frontal theta (brain activity with an oscillation rhythm in the frequency band 3.5–7.5 Hz) is consistently associated with heightened engagement during skilled motor performance (Kao et al. 2013) or video game play (Ewing et al. 2016; Nagendra et al. 2017; Salminen and Ravaja 2008; Yamada 1998). More recently, the Engagement Index (EI; Pope et al. 1995)—a ratio of theta, alpha (brain oscillations in the band 7.5–12.5 Hz), and beta (frequency band 12.5–25 Hz) EEG activity—has also been used to measure engagement in video game play (McMahan et al. 2015; Nagendra et al. 2017). While EEG has been used to evaluate spatial processing (Baumgartner et al. 2006; Kober et al. 2012) and motor function (Calabro et al. 2017; Lee et al. 2015; Oliveira et al. 2018) in a VR environment, EEG has not been used to evaluate VR engagement.

EEG metrics such as EI or frontal theta may also prove to be valid measures of VR engagement, but this has not yet been formally tested. These EEG metrics have historically been obtained using conventional multi-channel recording arrays, which can be cumbersome to use (Badcock et al. 2013; Johnstone et al. 2012), redundant (Schleiger et al. 2014), and poorly tolerated by neurological patients (Badcock et al. 2013; Johnstone et al. 2012). Alternatively, single-channel EEG systems offer a simple and efficient means of data collection while maintaining data quality (Johnstone et al. 2012) and reliability (Rogers et al. 2016), and would appear suited for acquiring EEG measurements of VR engagement.

The aim of the present study was therefore to provide a proof of concept of a single-channel device to obtain EEG indices of user engagement in VR. Prior to proceeding with a clinical study, a convenience sample of young, healthy adults was recruited to ensure the study methodology was sufficiently sensitive, and to help avoid wasting the time of stroke survivors and their families and carers. We compared EEG metrics between two *resting* conditions designed to elicit low levels of engagement and two *simulation* conditions designed to elicit higher levels of engagement. We predicted that healthy controls would exhibit a significant difference in frontal theta values and EI scores as a function of task condition. Also, we predicted that these EEG metrics would positively correlate with a standard self-report measure of virtual presence/engagement in a validated VR activity.

## 2 Materials and methods

This study was approved by the institutional ethics committee of the Australian Catholic University (HREC No: 2017-78E), and performed in accordance with their guidelines.

### 2.1 Participants

Twenty-five participants (17 female, *M*age = 26.7 years, range 18–47 years) were recruited from a university population in Australia. Eligible participants were English speaking and in good health, with no reported history of head injury, psychiatric disorder, neurological disorder, cardiovascular disease, or substance abuse. All participants were right-handed, with normal hearing and normal or corrected to normal vision.

### 2.2 VR system

*Elements* DNA (or EDNA) is a virtual-reality-based tabletop-mounted VR system that affords an embodied and playful form of interaction via goal-directed and exploratory tasks to train manual skills and volition. Previous evaluations of the EDNA system have identified strong improvements in motor, cognitive, and everyday performance in various forms of neuro-disability including hemiplegia through childhood cerebral palsy and stroke (Green and Wilson 2012, 2014), and traumatic brain injury and stroke in adults (Mumford et al. 2010, 2012; Rogers et al. 2019). The EDNA display technology consists of a 3MTM 42-inch LCD touchscreen, with integrated computer, multi-touch capacity, and marker-based tracking (Duckworth et al. 2015). Presented on the display is the EDNA training environment and tasks (Fig. 1), a series of four goal-directed and three exploratory movement activities (Mumford et al. 2010), including: *Bases*, consisting of a home base and four potential target locations. The circular targets are cued in a fixed order (east, north, west, south) using an illuminated border; *Random Bases*, with the same configuration of targets, but highlighted in random order; *Go*, consisting of a target circle appearing randomly in one of nine locations configured along three radials emanating from the home base; *Go-No-Go*, which uses the same target positions as *Go*, however, additional distractor shapes appear. Participants are instructed to respond to circular targets only and resist moving to distractors; and *Mixer*, *Squiggles*, and *Swarm*, tasks which are creative in nature, requiring participants to create novel audio-visual effects through active manual manipulation of tangible interfaces.

### 2.3 Task conditions

Continuous EEG was recorded during two *resting* and two *simulation* conditions, each 2-min in duration. The *resting* eyes-closed (rEC) condition required the participant to sit with their eyes closed. The *resting* eyes-open (rEO) condition presented a video of white circles rotating clockwise on a black background. The first *simulation* condition presented video (with sound) of a roller coaster ride (sRC), from a first-person perspective, sourced from YouTube (https://www.youtube.com/watch?v=q90JsglUY0U). A roller coaster scenario has often been used in the assessment of engagement-related phenomenon (Baumgartner et al. 2008; Freeman et al. 1999; Jäncke et al. 2009). The second *simulation* condition (sVR) comprised a sequence of videos (with sound), from a first-person perspective, showing performance of manual training tasks (Bases, Go, Squiggles, and Swarm) from the EDNA VR system (Green and Wilson 2012; Mumford et al. 2010, 2012).

### 2.4 Engagement self-report

The Presence Questionnaire (PQ) version 3 (https://docplayer.net/52991659-Presence-questionnaire-witmer-singer-vs-3-0-nov-1994-revised-by-the-uqo-cyberpsychology-lab-2004.html) is a 24-item self-report questionnaire designed to measure the degree of presence experienced in a virtual environment ($\alpha = 0.88$), encompassing four factors: Involvement; Adaptation/Immersion; Sensory Fidelity; and Interface Quality (Witmer et al. 2005; Witmer and Singer 1998). Using a 7-point Likert-type scale, higher scores indicate greater user engagement (max. = 168).

### 2.5 EEG acquisition and analysis

Continuous EEG was collected during repeated 2-min conditions using the NeuroSky MindWave device (NeuroSky™, CA, USA). The MindWave device continuously samples EEG data at 512 samples per second from a single dry stainless-steel electrode positioned at the International 10–20 system site FP1, referenced to the left earlobe. Raw EEG data were transmitted wirelessly via Bluetooth to a laptop computer for off-line analysis in MatLab (Release 2017a;

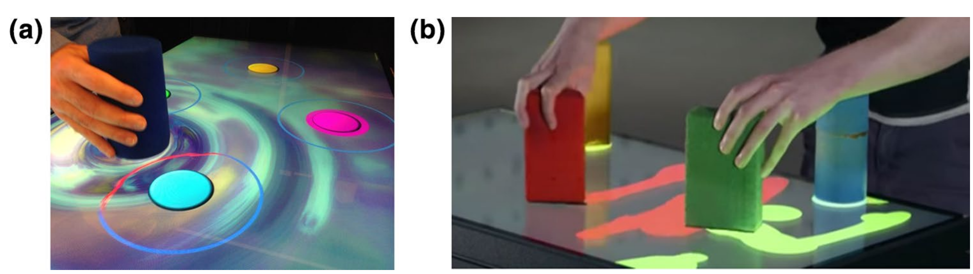


**Fig. 1** The tangible user interfaces and tabletop virtual environment in the **a** bases and **b** squiggles tasks of the *Elements DNA* virtual reality system

The MathWorks Inc, Natick MA), using functions from the "Signal Processing" and "Statistics, and Machine Learning" toolboxes. The raw EEG waveform was bandpass-filtered (4th order Butterworth, 0.5–30 Hz) and baseline-corrected. Eye-blink artefact correction was performed using Iterative Template Matching and Suppression (ITMS), an algorithm that automatically detects and suppresses eye-blink artefacts from a single-channel EEG (Valderrama et al. 2018). The EEG waveform was segmented into contiguous 2-sec epochs (0.5 Hz spectral resolution; 50% overlap), and any epochs containing amplitudes in excess of ± 150 µV were automatically rejected. Denoised epochs were applied a Hamming window of the same duration, transformed to the frequency domain through the fast Fourier transform (FFT), magnitude-squared, and averaged in order to obtain the power spectral density from which the absolute spectral power was estimated in the four classical frequency bands: delta (0.5–3.5 Hz), theta (3.5–7.5 Hz), alpha (7.5–12.5 Hz), and beta (12.5–25 Hz). *Relative power* was calculated by summing absolute power across the four bands to compute the total power, and then dividing the absolute power for each individual band by the total power, expressed as a percentage. Finally, relative power in the relevant bands was used to calculate EI, defined as beta/(alpha + theta).

## 2.6 Procedure

Each participant provided written informed consent for voluntary participation. Testing took place in a quiet room free from distraction, at the university, with all tasks administered by the second author, following training in EEG and VR from the first and senior authors, respectively. Participants were tested individually in a single session lasting approximately 45 min, divided into two parts. In part one, participants were fitted with the MindWave device. After minimising impedance levels, participants completed the four task conditions (rEC, rEO, sRC, sVR), with the order of administration counterbalanced. Participants were not moving objects during these conditions, only observing. Conditions were presented on a 42-inch, high-definition television monitor, positioned at eye level, 1 m from the seated participant. Audio was presented through paired external speakers (Logitech™) positioned at 30 cm to each side of the display and set at a comfortable audible level (approximately 60 dB). In part two, participants completed a total of 10 min of guided participation on the EDNA VR system, playing with both goal-directed and exploratory tasks. Immediately afterwards, participants completed the PQ in reference to their experience of using the EDNA system.

## 2.7 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics for Windows version 24 (IBM Corp, Armonk, NY). All data were checked for normality using Shapiro–Wilk's tests, where violations were detected, and the nonparametric alternative (e.g. Friedman test, Wilcoxon test) was applied. A series of one-way repeated measures ANOVAs examined the differential effect of task condition (rEC, rEO, sRC, sVR) on each of the four EEG frequency bands (delta, theta, alpha, beta) and the EI metric. Post hoc contrasts were conducted using Bonferroni adjustments ($p < 0.008$ for six multiple comparisons). EEG measures that showed condition effects were then included in a one-tailed Spearman's rank-order correlation analysis with the PQ total score.

# 3 Results

Complete data were available from 24 participants; due to an EEG recording issue, data from one participant was excluded from analysis. EEG data from the four task conditions are presented in Table 1. Following the session with the EDNA VR system, participants' average self-reported engagement, as measured by the PQ total score, was 137 ($SD = 14$, range 103–160).

There was no main effect of condition on the delta [$F(3,69) = 0.77$, $p = 0.51$] or beta [$\chi^2(3) = 6.64$, $p = 0.08$] power bands. In contrast, the condition effect was significant for the theta [$F(3,69) = 21.59$, $p < 0.01$, partial $\eta^2 = 0.48$] and

**Table 1** Valid epochs and EEG metrics (mean, 95% confidence interval) for each of the four experimental conditions

| Condition | Delta* | Theta* | Alpha* | Beta* | EI | Valid epochs |
|---|---|---|---|---|---|---|
| *Resting* | | | | | | |
| Eyes closed | 30.18 [27.49,32.87] | 26.93 [25.98,27.88] | 27.61 [24.89,30.32] | 14.89 [13.51,16.27] | 27.54 [24.60,30.48] | 49.79 |
| Eyes open | 30.78 [28.73,32.84] | 28.60 [27.52,29.68] | 24.79 [23.15,26.43] | 15.81 [14.26,17.37] | 29.89 [26.29,33.49] | 29.08 |
| *Simulation* | | | | | | |
| Rollercoaster | 31.07 [29.39,32.74] | 30.53 [29.57,31.50] | 23.08 [22.07,24.09] | 15.32 [13.95,16.70] | 28.69 [25.86,31.53] | 23.35 |
| EDNA VR | 31.81 [29.90,33.71] | 30.02 [29.11,30.93] | 22.64 [21.64,23.65] | 15.40 [13.85,16.96] | 29.44 [25.99,32.89] | 30.33 |

*EI* Engagement Index; EDNA VR: *Elements* DNA virtual rehabilitation

*Relative power

alpha bands [$F(3,69) = 9.20$, $p < 0.01$, partial $\eta^2 = 0.29$], and EI scores [$\chi^2(3) = 12.19$, $p < 0.01$]. After correcting for multiple comparisons, none of the post hoc differences for EI scores reached statistical significance. Post hoc testing (Table 2) did identify significant increases ($p < 0.008$) in relative theta band power from the *resting* (rEC and rEO) to the *simulation* conditions (sRC and sVR). The increase in frontal theta band activity was equivalent for both the roller coaster and the EDNA VR simulations. For frontal alpha band power, there was a significant decrease ($p \le 0.005$) from the *resting* conditions (rEC and rEO) to the *simulation* EDNA VR task, and from the *resting* eyes-closed task to the *simulation* roller coaster task ($p = 0.005$).

Based on the condition effects, theta and alpha band relative power data were entered into correlational analysis with PQ total scores (Table 3). Positive correlations were found between PQ total scores and relative power of theta in the two *simulation* conditions [sVR, $r_s = 0.38$, $p = 0.04$; sRC, $r_s = 0.48$, $p = 0.02$], suggesting a *moderate* association between an EEG biomarker of engagement (theta) and a self-report measure of engagement (PQ total score). Additionally, there was a negative association between theta and alpha in the resting eyes closed [$r_s = -0.46$, $p = 0.01$] and resting eyes-open conditions [$r_s = -0.39$, $p = 0.03$], consistent with the expected sensitivity of these EEG frequencies to standard variations in resting state task conditions (Barry et al. 2007; Barry et al. 2014).

## 4 General discussion

Engagement in rehabilitation is a multi-dimensional phenomenon (Bright et al. 2015), driven by personal factors such as the motivation and active participation of the patient

**Table 2** Post hoc contrast analysis significance tests ($p$ values) for the four EEG conditions on theta and alpha relative power

| Comparison | | Theta | | Alpha | |
|---|---|---|---|---|---|
| | | *p* Value | *d* Value | *p* Value | *d* Value |
| VR simulation vs. | Rollercoaster simulation | 0.128 | | 0.391 | |
| | Resting eyes closed | < 0.001* | 1.40 | 0.001* | 1.02 |
| | Resting eyes open | 0.001* | 0.60 | 0.005* | 0.67 |
| Rollercoaster simulation vs. | VR simulation | 0.128 | | 0.391 | |
| | Resting eyes closed | < 0.001* | 1.59 | 0.005* | 0.93 |
| | Resting eyes open | 0.001* | 0.79 | 0.023 | |
| Resting eyes closed vs. | VR simulation | < 0.001* | 1.40 | 0.001* | 1.02 |
| | Rollercoaster simulation | < 0.001* | 1.59 | 0.005* | 0.93 |
| | Resting eyes open | 0.002* | 0.70 | 0.027 | |
| Resting eyes open vs. | VR simulation | 0.001* | 0.60 | 0.005* | 0.67 |
| | Rollercoaster simulation | 0.001* | 0.79 | 0.023 | |
| | Resting eyes closed | 0.002* | 0.70 | 0.027 | |

Cohen's *d* effect sizes are presented for significant differences ($p < 0.008$)

**Table 3** Spearman rank-order correlations (one-tailed) between self-reported engagement (Presence Questionnaire) and EEG metrics (theta relative power, alpha relative power)

| | sVR theta | sRC theta | rEC theta | rEO theta | sVR alpha | sRC alpha | rEC alpha | rEO alpha | PQ |
|---|---|---|---|---|---|---|---|---|---|
| sVR theta | – | | | | | | | | |
| sRC theta | 0.77** | – | | | | | | | |
| rEC theta | 0.41* | 0.10 | – | | | | | | |
| rEO theta | 0.65** | 0.42* | 0.56** | – | | | | | |
| sVR alpha | 0.25 | 0.04 | 0.12 | 0.03 | – | | | | |
| sRC alpha | − 0.14 | − 0.31 | 0.17 | − 0.22 | 0.26 | – | | | |
| rEC alpha | 0.13 | 0.30 | − 0.46* | − 0.25 | − 0.02 | − 0.19 | – | | |
| rEO alpha | 0.04 | 0.01 | − 0.08 | − 0.39* | 0.39* | 0.49** | 0.35* | – | |
| PQ | 0.38* | 0.48* | 0.19 | 0.11 | 0.06 | 0.10 | 0.03 | 0.20 | – |

*PQ* Presence questionnaire; *rEC* resting eyes-closed condition; *rEO* resting eyes-open condition; *sVR elements* DNA virtual rehabilitation simulation condition; *sRC* roller coaster simulation condition

*$p < 0.05$, **$p < 0.001$

(Brett et al. 2017; Lequerica et al. 2009), environmental factors associated with the setting and therapeutic alliance, and task factors associated with the rehabilitation activities (Bartur et al. 2017; Burke et al. 2009a). Greater levels of engagement are predictive of positive outcomes, as engagement fosters the transfer of trained skills and knowledge to corresponding real-world behaviour (Kober et al. 2012). Therefore, as the emerging field of VR seeks to build an evidence base to inform design and validate clinical efficacy, there is an increasing need for robust methods for determining when individuals are sufficiently engaged. However, given its subjective nature, assessment of engagement is a challenging task (McMahan et al. 2015). As an alternative to self-report questionnaires, single-channel EEG technology may offer an easy (Ekandem et al. 2012) and efficacious (Johnstone et al. 2012; Rogers et al. 2016) neurophysiological measure of an individual's level of engagement. In the current study, frontal theta was particularly sensitive to task manipulations in the level of engagement, and was associated with the subjective self-reported level of engagement, providing converging evidence in support of its use as a measure of user engagement in VR simulation and participation. These results are discussed, in turn, below.

### 4.1 Theta as a measure of engagement

Augmented frontal theta is associated with cognitive control and working memory function (Cavanagh and Frank 2014; Hsieh and Ranganath 2014), and focused (Doppelmayr et al. 2008) and sustained attention (Fairclough and Venables 2006; Fairclough et al. 2005). The relationship between theta and these aspects of mental effort have led to the uptake of frontal theta band activity as an index of engagement in flight and air traffic control simulations (Borghini et al. 2011; Dussault et al. 2005; Smith et al. 2001) and the video gaming literature (Ewing et al. 2016; Nagendra et al. 2017; Salminen and Ravaja 2008; Yamada 1998), but has yet to be applied in VR research.

In the current study, theta obtained from a single, left pre-frontal electrode was sensitive to manipulations in a series of VR-related activities, with the less engaging, *resting* conditions (rEC and rEO) associated with lower relative power in the theta band, and the more engaging roller coaster *simulation* condition (sRC) associated with greater theta band activity. This pattern of theta modulation was consistent with previous reports of the impact of more and less immersive virtual reality environments (Slobounov et al. 2015), but findings had not previously been linked with the concept of engagement.

Encouragingly, theta band activity during the EDNA condition (sVR) was comparable to the roller coaster condition (sRC), providing preliminary criterion-related evidence of the enhanced level of engagement that can be facilitated by a VR approach. Furthermore, theta band power in the roller coaster and EDNA conditions also corresponded to engagement levels measured on the PQ, a standard self-report questionnaire. The PQ has been repeatedly endorsed as a valid and reliable measure of presence and engagement in a variety of contexts (Brackney and Priode 2017; Deutsch et al. 2013; Gamito et al. 2010; Witmer et al. 2005), and the questionnaire offers superior psychometrics to the various one-item Likert scales that have been utilised in past research (e.g. Baumgartner et al. 2008; Freeman et al. 1999; Kober et al. 2012; Slobounov et al. 2015). The similar pattern of modulation in theta band power activity and subjective self-report offers encouraging preliminary face validity that single-channel EEG changes in frontal theta band activity express variations in VR engagement.

In the current study, the *simulation* EEG conditions were also differentiated from the *resting* EEG conditions by a significant decrease in alpha band activity. These findings are consistent with previous observations that frontally distributed alpha band power is prominent during relaxed conditions at decreased attention levels, and attenuates during more complex and cognitively demanding tasks (Fairclough et al. 2005; Slobounov et al. 2000) and less immersive virtual reality environments (Kober et al. 2012). The two-factor pattern identified in the current study, comprised of a decrease in alpha *and* an increase in theta activity, has also previously been described (Smith et al. 2001), and connected to enhanced accuracy of performance (Klimesch 1999). However, alpha power in the current study was not correlated with PQ self-report. At frontal electrode sites, this EEG frequency therefore appears to reflect bottom-up variations in attention and arousal (Barry et al. 2007; Barry et al. 2014), likely related to the amount of visual scanning (Gundel and Wilson 1992), rather than top-down levels of VR engagement. Finally, as expected, no significant difference in delta and beta band activity was detected across the different EEG conditions. These frequency bands are associated with states of sleep or deep restfulness (delta) and heavy cognitive load (beta) that were not induced by the conditions in the current study.

### 4.2 EI as a measure of engagement

Contrary to expectation, EI scores (the ratio of beta to alpha + theta) in the current study were not sensitive to variations in the *resting* and *simulation* EEG conditions. Notably, previous reports of the association between EI scores and engagement were derived from multi-channel EEG systems (McMahan et al. 2015; Pope et al. 1995), while the current study relied upon a single pre-frontal electrode. The subjective experience of engagement in virtual environments has been linked to activity within a distributed fronto-parietal network, including down-regulation of pre-frontal inhibitory control mechanisms, and increased activation of parietal sensory processing centres (Baumgartner et al. 2006, 2008). A global EEG index such as EI, derived from the grand averaged band power across a multi-channel array, may be well suited for monitoring activity within this network. However, EI does not appear to be the optimal algorithm for calculating user engagement levels from a single pre-frontal channel EEG system, which lacks central and posterior electrode sites.

### 4.3 Limitations and Future directions

While there is an increasing body of literature suggesting that engagement can be measured via EEG paradigms, there are no well-established methodologies and agreed-upon evaluation procedures. The meaning of "engagement" itself remains loosely articulated, with the term linked variously to attributes of flow theory (Csikszentmihalyi 1990), aesthetic theory (Beardsely 1982), play theory (Stephenson 1967), and information interaction (Toms 2002). Acknowledging the contribution of all of these theories, O'Brien and Toms (O'Brien and Toms 2008) have proposed a unifying framework for engagement comprised of core attributes including focused attention, system feedback, user control, activity orientation, and intrinsic motivation; importantly, the current study utilised an engagement questionnaire with a factor structure (involvement; immersion; sensory fidelity; interface quality) well aligned to this model (Witmer et al. 2005).

In view of existing problems with movement artefacts during EEG measurements (Reinecke et al. 2011), the evaluation of VR tasks and exercises is more limited to simulation exercises that involve negligible movement. The current study therefore acquired EEG during the observation rather than the completion of EDNA tasks and exercises, and we acknowledge the two processes are not equivalent. However, neuroimaging studies suggest mental representations of an action can be activated by virtual reality stimuli without the execution of overt actions (Baumgartner et al. 2007; Jäncke et al. 2009). Hence, the experience of engagement with the EDNA system can be induced while only *observing* VR tasks, with resultant variations in the EEG corresponding to self-reported engagement while *completing* VR tasks. Moreover, action observation and mental rehearsal themselves have been used as an effective rehabilitation strategy for severe brain injury (Ruffino et al. 2017).

In addition to body movement, EEG from a single-channel device can be susceptible to eye-blink and eye-movement artefacts (Ratti et al. 2017). In the current study, while eye-blink artefacts could be suppressed by the ITMS method (Valderrama et al. 2018), epochs containing eye-movement artefacts were simply rejected. This results in data loss, and the eyes-closed condition contained nearly double the number of valid epochs as each of the eyes-open conditions ($49.79 \pm 18.30$ c.f. $27.56 \pm 15.31$). However, using tasks 2 min long, the average number of valid epochs in each condition was well above the inclusion level for analysis (Johnstone et al. 2012). Longer EEG acquisition time frames may be advisable in future trials involving participant populations anticipated to be susceptible to eye-movement artefacts (e.g. eye or neck dystonia).

Furthermore, the current study utilised a convenience sample of healthy adults, rather than the target population of stroke survivors, as it was deemed inappropriate to proceed to recruitment of a clinical population without first establishing proof of concept. Participants were therefore far younger and healthier than a typical survivor of stroke (Feigin et al. 2017). As EEG activity changes over the lifespan (Barry et al. 2014; Zappasodi et al. 2015) and after a stroke (Finnigan et al. 2016), the current findings require replication in the target clinical population before theta obtained from a single, left pre-frontal electrode can be confidently offered as a measure of post-stroke VR engagement, and a potential alternative to subjective self-report.

The motivational intensity model (Ewing et al. 2016; Wright 2008) provides a conceptual framework for defining states of engagement, based upon the relationship between task demands and user effort. The ideal level of engagement is characterised by a degree of task demand and skill development that is sufficient to avoid boredom, but not so great that the user experiences "overload," making task mastery or competence unlikely, and withdrawing effort. While the current study suggests single-channel theta EEG power can detect the threshold between boredom (i.e. the absence of engagement) and engagement, further work is required to establish single-channel indices of the upper limit between engagement and overload. Awareness of both lower and upper thresholds will be crucial in the design of effective and responsive VR paradigms that can keep patients continuously engaged (Bartur et al. 2017; McMahan et al. 2015).

Finally, in the context of stroke rehabilitation, it is important to recognise that patient *attendance* in a rehabilitation programme does not automatically equate to patient *engagement* with the rehabilitation program (Imms et al. 2017; Li et al. 2016). Li and colleagues (Li et al. 2016) have argued that evaluation of engagement should consider four separate, but inter-related aspects: motor engagement, perceptive engagement, cognitive engagement, and emotional engagement. Indicators of motor engagement can include electromyography (Zimmerli et al. 2013) and kinematic measures (Li et al. 2014), perceptive engagement can be monitored via eye-blinking activity (Yamada 1998) and eye tracking systems (Miller 2015), indices of positive emotion (Ostir et al. 2008; Seale et al. 2010) can be used to track emotional engagement, and EEG measures can be utilised as an indicator of cognitive engagement (Ewing et al. 2016; Kao et al. 2013; Nagendra et al. 2017; Salminen and Ravaja 2008;

Yamada 1998). While this engagement evaluation model requires external validation, the approach is consistent with calls for multiple measures and mixed methods (Lalmas et al. 2014), and the current study likely captures just one facet of the multi-dimensional construct of user engagement.

## 5 Conclusions

There has been a rapid growth in the use of virtual reality for health purposes, including enhancement of post-stroke motor and cognitive rehabilitation (Aminov et al. 2018). The success of VR approaches such as EDNA in this arena will depend, in part, on the capability of virtual reality applications to facilitate patient engagement (Slobounov et al. 2015). The current findings suggest that modulation of frontal theta, obtained from a single channel of EEG, expresses the subjective sense of presence induced by the EDNA system. These preliminary findings provide proof of concept of an objective approach for measuring a key component of engagement in VR, which will be of value in elucidating the impact of system design and implementation factors, and evaluating the efficacy of VR as a clinical intervention.

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### Compliance with ethical standards

**Conflict of interest** The authors have no conflict of interest to report.

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