

Proof of concept of a single-channel EEG measure of engagement in virtual rehabilitation

Jeffrey M. Rogers^a, Jenny Jensen^b, Joaquin T. Valderrama^{c,d,e}, Stuart J. Johnstone^f, and Peter H. Wilson^g

^aThe University of Sydney, Faculty of Health Sciences, Sydney NSW, Australia. ORCID 0000-0002-0320-969X

^bAustralian Catholic University, School of Behavioural and Health Sciences, Melbourne VIC, Australia.

^cNational Acoustic Laboratories Sydney NSW, Australia. ORCID 0000-0002-5529-8620

^dDepartment of Linguistics, Macquarie University, NSW Sydney, Australia

^eThe HEARing CRC, Melbourne VIC, Australia.

^fUniversity of Wollongong, School of Psychology and Brain & Behaviour Research Institute, Wollongong NSW, Australia. ORCID 0000-0001-5380-9952

^gAustralian Catholic University, School of Behavioural and Health Sciences and Centre for Disability and Development Research, Melbourne VIC, Australia. ORCID 0000-0003-3747-0287

Corresponding author: Prof Peter Wilson, School of Behavioural and Health Sciences, Australian Catholic University, 115 Victoria Parade, Melbourne VIC 3450, Australia. Tel.: +61 3 9953-3445; E-mail address: peterh.wilson@acu.edu.au

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1 **ABSTRACT**

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

20
21 **Key words:** engagement; presence; electroencephalogram; rehabilitation; virtual-reality

22
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1 1. INTRODUCTION

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

14

15 Virtual reality approaches have been developed to increase motivation to participate in
16 rehabilitation by presenting exercises in an enjoyable, interactive, and novel manner
17 (Duckworth et al. 2015; Howard 2017; Mumford et al. 2012; Rogers et al. 2019). Based on
18 virtual reality simulation and interactive technologies, and informed by neuroscience and
19 learning theory, these so-called “virtual rehabilitation” (VR) approaches attempt to maximise
20 user engagement by the provision of: (1) an *enriched therapeutic environment* (Perez et al.
21 2004) that both affords action and engages the patient’s cognitive attention; (2) *augmented*
22 *feedback* in real time and after performance (Maier et al. 2019; Zimmerli et al. 2013) to
23 enhance motor learning and future movement planning; and (3) in-system scaling of the level
24 of task challenge (Schultheis and Rizzo 2001), ensuring *dynamic scaffolding* of the user’s
25 processing and response capabilities.

26

27 Meta-analyses of post-stroke VR interventions have repeatedly revealed the approach is more
28 beneficial for recovery than conventional therapies (Aminov et al. 2018; Laver et al. 2017;
29 Lohse et al. 2014; Palma et al. 2017). Additional reviews have identified principles of motor
30 (e.g. variable practice, implicit and explicit feedback, increasing intensity) and social
31 cognitive learning (e.g. vicarious learning, performance accomplishment) presumed to
32 underlie the positive effect of post-stroke VR (Imam and Jarus 2014; Maier et al. 2019).
33 However, despite an evidence-based approach to the development of VR, and much
34 deliberation about the active ingredients of VR that may contribute to engagement (Burke et
35 al. 2009b; Levin 2011; Lewis and Rosie 2012; Zimmerli et al. 2013), there is little work
36 formally evaluating whether VR approaches can, in fact, enhance patient engagement.
37 Engagement is often assessed via self-report measures of the subjective experience of
38 *presence* (Barello et al. 2012; Kober et al. 2012). Presence refers to the subjective experiences
39 mediated by an environment, including the extent to which it engages our senses, captures our
40 attention, and fosters our active involvement (Witmer et al. 2005).

41

42 However, self-report approaches require attention, comprehension, self-reflection, and
43 communication skills that are often compromised after stroke and other neurological injuries.
44 Alternatively, electrophysiological methods can provide an objective measure of a user's
45 immediate responses to VR, which correlate with traditional self-report measures of
46 engagement (Leiker et al. 2016; Zimmerli et al. 2013). In particular, the electroencephalogram
47 (EEG) can provide real-time information on brain activity, with the level of task engagement
48 reliably associated with EEG indices of attentional allocation, visual interpretation, and
49 information processing (Berka et al. 2007). Specifically, increased frontal theta (brain activity
50 with an oscillation rhythm in the frequency band 3.5-7.5 Hz) is consistently associated with
51 heightened engagement during skilled motor performance (Kao et al. 2013) or video game
52 play (Ewing et al. 2016; Nagendra et al. 2017; Salminen and Ravaja 2008; Yamada 1998).

53 More recently, the Engagement Index (EI; Pope et al. 1995) - a ratio of theta, alpha (brain
54 oscillations in the band 7.5-12.5 Hz), and beta (frequency band 12.5-25 Hz) EEG activity -
55 has also been used to measure engagement in video game play (McMahan et al. 2015;
56 Nagendra et al. 2017). While EEG has been used to evaluate spatial processing (Baumgartner
57 et al. 2006; Kober et al. 2012) and motor function (Calabro et al. 2017; Lee et al. 2015;
58 Oliveira et al. 2018) in a VR environment, EEG has not been used to evaluate VR engagement.

59

60 EEG metrics such as EI or frontal theta may also prove to be valid measures of VR
61 engagement, but this has not yet been formally tested. These EEG metrics have historically
62 been obtained using conventional multi-channel recording arrays, which can be cumbersome
63 to use (Badcock et al. 2013; Johnstone et al. 2012), redundant (Schleiger et al. 2014), and
64 poorly tolerated by neurological patients (Badcock et al. 2013; Johnstone et al. 2012).
65 Alternatively, single-channel EEG systems offer a simple and efficient means of data
66 collection while maintaining data quality (Johnstone et al. 2012) and reliability (Rogers et al.
67 2016), and would appear suited for acquiring EEG measurements of VR engagement.

68

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

80 2. MATERIAL AND METHODS

81 This study was approved by the institutional ethics committee of the Australian Catholic
82 University (HREC N^o: 2017-78E), and performed in accordance with their guidelines.

83

84 2.1 Participants

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

90

91 2.2 VR System

92 *Elements DNA* (or EDNA) is a virtual-reality based tabletop-mounted VR system that affords
93 an embodied and playful form of interaction via goal-directed and exploratory tasks to train
94 manual skills and volition. Previous evaluations of the EDNA system have identified strong
95 improvements in motor, cognitive, and everyday performance in various forms of neuro-
96 disability including hemiplegia through childhood cerebral palsy and stroke (Green and
97 Wilson 2014; Green and Wilson 2012), and traumatic brain injury and stroke in adults
98 (Mumford et al. 2010; Mumford et al. 2012; Rogers et al. 2019). The EDNA display
99 technology consists of a 3MTM 42-inch LCD touchscreen, with integrated computer, multi-
100 touch capacity, and marker based tracking (Duckworth et al. 2015). Presented on the display
101 is the EDNA training environment and tasks (Figure 1), a series of four goal-directed and
102 three exploratory movement activities (Mumford et al. 2010), including: *Bases*, consisting of
103 a home base and four potential target locations. The circular targets are cued in a fixed order
104 (east, north, west, south) using an illuminated border; *Random Bases*, with the same

105 configuration of targets, but highlighted in random order; *Go*, consisting of a target circle
106 appearing randomly in one of nine locations configured along three radials emanating from
107 the home base; *Go-No-Go*, which uses the same target positions as *Go*, however, additional
108 distractor shapes appear. Participants are instructed to respond to circular targets only and
109 resist moving to distractors; and *Mixer*, *Squiggles*, and *Swarm*, tasks which are creative in
110 nature, requiring participants to create novel audio-visual effects through active manual
111 manipulation of tangible interfaces.

112

113 **2.3 Task Conditions**

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

125

126 **2.4 Engagement self-report**

127 The Presence Questionnaire (PQ) version 3 ([https://docplayer.net/52991659-Presence-](https://docplayer.net/52991659-Presence-questionnaire-witmer-singer-vs-3-0-nov-1994-revised-by-the-uqo-cyberpsychology-lab-2004.html)
128 [questionnaire-witmer-singer-vs-3-0-nov-1994-revised-by-the-uqo-cyberpsychology-lab-](https://docplayer.net/52991659-Presence-questionnaire-witmer-singer-vs-3-0-nov-1994-revised-by-the-uqo-cyberpsychology-lab-2004.html)
129 [2004.html](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
130 experienced in a virtual environment ($\alpha = 0.88$), encompassing four factors: Involvement;

131 Adaptation/Immersion; Sensory Fidelity; and Interface Quality (Witmer et al. 2005; Witmer
132 and Singer 1998). Using a 7-point Likert-type scale, higher scores indicate greater user
133 engagement (max. = 168).

134

135 **2.5 EEG acquisition and analysis**

136 Continuous EEG was collected during repeated 2-min conditions using the NeuroSky
137 MindWave device (NeuroSky™, CA, USA). The MindWave device continuously samples
138 EEG data at 512 samples per second from a single dry stainless-steel electrode positioned at
139 the International 10-20 system site FP1, referenced to the left earlobe. Raw EEG data was
140 transmitted wirelessly via Bluetooth to a laptop computer for off-line analysis in MatLab
141 (Release 2017a; The MathWorks Inc, Natick MA), using functions from the “Signal
142 Processing” and “Statistics, and Machine Learning” toolboxes. The raw EEG waveform was
143 bandpass filtered (4th order Butterworth, 0.5-30 Hz) and baseline corrected. Eye-blink artefact
144 correction was performed using Iterative Template Matching and Suppression (ITMS), an
145 algorithm that automatically detects and suppresses eye-blink artefacts from a single-channel
146 EEG (Valderrama et al. 2018). The EEG waveform was segmented into contiguous 2-sec
147 epochs (0.5 Hz spectral resolution; 50% overlap), and any epochs containing amplitudes in
148 excess of $\pm 150\mu\text{V}$ were automatically rejected. Denoised epochs were applied a Hamming
149 window of the same duration, transformed to the frequency domain through the Fast Fourier
150 Transform (FFT), magnitude squared, and averaged in order to obtain the power spectral
151 density from which the absolute spectral power was estimated in the four classical frequency
152 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).
153 *Relative power* was calculated by summing absolute power across the four bands to compute
154 the total power, and then dividing the absolute power for each individual band by the total
155 power, expressed as a percentage. Finally, relative power in the relevant bands was used to
156 calculate EI, defined as $\text{beta}/(\text{alpha}+\text{theta})$.

157

158 **2.6 Procedure**

159 Each participant provided written informed consent for voluntary participation. Testing took
160 place in a quiet room free from distraction, at the university, with all tasks administered by
161 the second author, following training in EEG and VR from the first and senior authors,
162 respectively. Participants were tested individually in a single session lasting approximately
163 45-min, divided into two parts. In part one, participants were fitted with the MindWave
164 device. After minimising impedance levels, participants completed the four task conditions
165 (rEC, rEO, sRC, sVR), with the order of administration counterbalanced. Participants were
166 not moving objects during these conditions, only observing. Conditions were presented on a
167 42-inch, high definition television monitor, positioned at eye level, 1 m from the seated
168 participant. Audio was presented through paired external speakers (LogitechTM) positioned at
169 30 cm to each side of the display and set at a comfortable audible level (approximately 60
170 dB). In part two, participants completed a total of 10 min of guided participation on the EDNA
171 VR system, playing with both goal-directed and exploratory tasks. Immediately afterward,
172 participants completed the PQ in reference to their experience of using the EDNA system.

173

174 **2.7 Statistical analysis**

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

183 PQ total score.

184 3. RESULTS

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

190

191 There was no main effect of condition on the delta [$F(3,69) = 0.77, p = 0.51$] or beta [$\chi^2(3) =$
192 $6.64, p = 0.08$] power bands. In contrast, the condition effect was significant for the theta
193 [$F(3,69) = 21.59, p < 0.01, \text{partial } \eta^2 = 0.48$] and alpha bands [$F(3,69) = 9.20, p < 0.01, \text{partial}$
194 $\eta^2 = 0.29$], and EI scores [$\chi^2(3) = 12.19, p < 0.01$]. After correcting for multiple comparisons,
195 none of the post-hoc differences for EI scores reached statistical significance. Post-hoc testing
196 (Table 2) did identify significant increases ($p < 0.008$) in relative theta band power from the
197 *resting* (rEC and rEO) to the *simulation* conditions (sRC and sVR). The increase in frontal
198 theta band activity was equivalent for both the rollercoaster and the EDNA VR simulations.
199 For frontal alpha band power, there was a significant decrease ($p \leq 0.005$) from the *resting*
200 conditions (rEC and rEO) to the *simulation* EDNA VR task, and from the *resting* eyes closed
201 task to the *simulation* rollercoaster task ($p = 0.005$).

202

203 Based on the condition effects, theta and alpha band relative power data were entered into
204 correlational analysis with PQ total scores (Table 3). Positive correlations were found between
205 PQ total scores and relative power of theta in the two *simulation* conditions [sVR, $r_s = 0.38, p$
206 $= 0.04$; sRC, $r_s = 0.48, p = 0.02$], suggesting a *moderate* association between an EEG
207 biomarker of engagement (theta) and a self-report measure of engagement (PQ total score).
208 Additionally, there was a negative association between theta and alpha in the resting eyes

209 closed [$r_s = -0.46, p = 0.01$] and resting eyes open conditions [$r_s = -0.39, p = 0.03$], consistent
210 with the expected sensitivity of these EEG frequencies to standard variations in resting state
211 task conditions (Barry et al. 2007; Barry et al. 2014).

212

213 **4. GENERAL DISCUSSION**

214 Engagement in rehabilitation is a multi-dimensional phenomenon (Bright et al. 2015), driven
215 by personal factors such as the motivation and active participation of the patient (Brett et al.
216 2017; Lequerica et al. 2009), environmental factors associated with the setting and therapeutic
217 alliance, and task factors associated with the rehabilitation activities (Bartur et al. 2017; Burke
218 et al. 2009a). Greater levels of engagement are predictive of positive outcomes, as
219 engagement fosters the transfer of trained skills and knowledge to corresponding real world
220 behaviour (Kober et al. 2012). Therefore, as the emerging field of VR seeks to build an
221 evidence base to inform design and validate clinical efficacy, there is an increasing need for
222 robust methods for determining when individuals are sufficiently engaged. However, given
223 its subjective nature, assessment of engagement is a challenging task (McMahan et al. 2015).
224 As an alternative to self-report questionnaires, single-channel EEG technology may offer an
225 easy (Ekandem et al. 2012) and efficacious (Johnstone et al. 2012; Rogers et al. 2016)
226 neurophysiological measure of an individual's level of engagement. In the current study,
227 frontal theta was particularly sensitive to task manipulations in the level of engagement, and
228 was associated with the subjective self-reported level of engagement, providing converging
229 evidence in support of its use as a measure of user engagement in VR simulation and
230 participation. These results are discussed, in turn, below.

231

232 **4.1 Theta as a measure of engagement**

233 Augmented frontal theta is associated with cognitive control and working memory function
234 (Cavanagh and Frank 2014; Hsieh and Ranganath 2014), and focused (Doppelmayr et al.

235 2008) and sustained attention (Fairclough and Venables 2006; Fairclough et al. 2005). The
236 relationship between theta and these aspects of mental effort have led to the uptake of frontal
237 theta band activity as an index of engagement in flight and air traffic control simulations
238 (Borghini et al. 2011; Dussault et al. 2005; Smith et al. 2001) and the video gaming literature
239 (Ewing et al. 2016; Nagendra et al. 2017; Salminen and Ravaja 2008; Yamada 1998), but has
240 yet to be applied in VR research.

241
242 In the current study, theta obtained from a single, left pre-frontal electrode was sensitive to
243 manipulations in a series of VR-related activities, with the less engaging, *resting* conditions
244 (rEC and rEO) associated with lower relative power in the theta band, and the more engaging
245 rollercoaster *simulation* condition (sRC) associated with greater theta band activity. This
246 pattern of theta modulation was consistent with previous reports of the impact of more and
247 less immersive virtual reality environments (Slobounov et al. 2015), but findings had not
248 previously been linked with the concept of engagement.

249
250 Encouragingly, theta band activity during the EDNA condition (sVR) was comparable to the
251 rollercoaster condition (sRC), providing preliminary criterion-related evidence of the
252 enhanced level of engagement that can be facilitated by a VR approach. Furthermore, theta
253 band power in the rollercoaster and EDNA conditions also corresponded with engagement
254 levels measured on the PQ, a standard self-report questionnaire. The PQ has been repeatedly
255 endorsed as a valid and reliable measure of presence and engagement in a variety of contexts
256 (Brackney and Priode 2017; Deutsch et al. 2013; Gamito et al. 2010; Witmer et al. 2005), and
257 the questionnaire offers superior psychometrics to the various one-item Likert scales that have
258 been utilised in past research (e.g., Baumgartner et al. 2008; Freeman et al. 1999; Kober et al.
259 2012; Slobounov et al. 2015). The similar pattern of modulation in theta band power activity
260 and subjective self-report offers encouraging preliminary face validity that single-channel

261 EEG changes in frontal theta band activity express variations in VR engagement.

262

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

279

280 **4.2 EI as a measure of engagement**

281 Contrary to expectation, EI scores (the ratio of beta to alpha+theta) in the current study were
282 not sensitive to variations in the *resting* and *simulation* EEG conditions. Notably, previous
283 reports of the association between EI scores and engagement were derived from multi-channel
284 EEG systems (McMahan et al. 2015; Pope et al. 1995), while the current study relied upon a
285 single pre-frontal electrode. The subjective experience of engagement in virtual environments
286 has been linked to activity within a distributed fronto-parietal network, including down-

287 regulation of prefrontal inhibitory control mechanisms, and increased activation of parietal
288 sensory processing centres (Baumgartner et al. 2008; Baumgartner et al. 2006). A global EEG
289 index such as EI, derived from the grand averaged band power across a multi-channel array,
290 may be well suited for monitoring activity within this network. However, EI does not appear
291 to be the optimal algorithm for calculating user engagement levels from a single pre-frontal
292 channel EEG system, which lacks central and posterior electrode sites.

293

294 **4.3 Limitations and Future directions**

295 While there is an increasing body of literature suggesting that engagement can be measured via
296 EEG paradigms, there are no well-established methodologies and agreed-upon evaluation
297 procedures. The meaning of “engagement” itself remains loosely articulated, with the term
298 linked variously to attributes of flow theory (Csikszentmihalyi 1990), aesthetic theory
299 (Beardsely 1982), play theory (Stephenson 1967), and information interaction (Toms 2002).
300 Acknowledging the contribution of all of these theories, O’Brien and Toms (O’Brien and Toms
301 2008) have proposed a unifying framework for engagement comprised of core attributes
302 including focused attention, system feedback, user control, activity orientation, and intrinsic
303 motivation; importantly, the current study utilized an engagement questionnaire with a factor
304 structure (involvement; immersion; sensory fidelity; interface quality) well aligned to this
305 model (Witmer et al. 2005).

306

307 In view of existing problems with movement artifacts during EEG measurements (Reinecke et
308 al. 2011), the evaluation of VR tasks and exercises is more limited to simulation exercises that
309 involve negligible movement. The current study therefore acquired EEG during the observation
310 rather than the completion of EDNA tasks and exercises, and we acknowledge the two
311 processes are not equivalent. However, neuroimaging studies suggest mental representations
312 of an action can be activated by virtual reality stimuli without the execution of overt actions

313 (Baumgartner et al. 2007; Jäncke et al. 2009). Hence, the experience of engagement with the
314 EDNA system can be induced while only *observing* VR tasks, with resultant variations in the
315 EEG corresponding to self-reported engagement while *completing* VR tasks. Moreover, action
316 observation and mental rehearsal themselves have been used as an effective rehabilitation
317 strategy for severe brain injury (Ruffino et al. 2017).

318

319 In addition to body movement, EEG from a single-channel device can be susceptible to eye-
320 blink and eye-movement artifacts. In the current study, while eye blink artifacts could be
321 suppressed by the ITMS method (Valderrama et al. 2018), epochs containing eye movement
322 artifacts were simply rejected. This results in data loss, and the eyes closed condition contained
323 nearly double the number of valid epochs as each of the eyes open conditions (49.79 ± 18.30 c.f.
324 27.56 ± 15.31). However, using tasks 2-min long, the average number of valid epochs in each
325 condition was well above the inclusion level for analysis, Longer EEG acquisition time frames
326 may be advisable in future trials involving participant populations anticipated to be susceptible
327 to eye movement artifacts (e.g. eye or neck dystonia).

328

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

337

338 The Motivational Intensity Model (Ewing et al. 2016; Wright 2008) provides a conceptual

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

349

350 Finally, in the context of stroke rehabilitation, it is important to recognise that patient
351 *attendance* in a rehabilitation program does not automatically equate to patient *engagement*
352 with the rehabilitation program (Imms et al. 2017; Li et al. 2016). Li and colleagues (Li et al.
353 2016) have argued that evaluation of engagement should consider four separate, but inter-
354 related aspects: motor engagement, perceptive engagement, cognitive engagement, and
355 emotional engagement. Indicators of motor engagement can include electromyography
356 (Zimmerli et al. 2013) and kinematic measures (Li et al. 2014), perceptive engagement can be
357 monitored via eye blinking activity (Yamada 1998) and eye tracking systems (Miller 2015),
358 indices of positive emotion (Ostir et al. 2008; Seale et al. 2010) can be used to track emotional
359 engagement, and EEG measures can be utilised as an indicator of cognitive engagement
360 (Ewing et al. 2016; Kao et al. 2013; Nagendra et al. 2017; Salminen and Ravaja 2008; Yamada
361 1998). While this engagement evaluation model requires external validation, the approach is
362 consistent with calls for multiple measures and mixed methods (Lalmas et al. 2014), and the
363 current study likely captures just one facet of the multidimensional construct of user
364 engagement.

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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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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
<i>Resting</i>						
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
<i>Simulation</i>						
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

Note: *Relative power. EI: Engagement Index; EDNA VR: *Elements* DNA virtual rehabilitation

Table 2. Post-hoc contrast analysis significance tests (*p* values) for the four EEG conditions on theta and alpha relative power. Cohen’s *d* effect sizes are presented for significant differences (*p* < 0.008).

Comparison		Theta		Alpha	
		<i>P</i> value	<i>d</i> value	<i>P</i> value	<i>d</i> 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	

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	-

Note. * $p < 0.05$, ** $p < 0.001$. PQ: Presence Questionnaire; rEC: resting eyes closed condition; rEO: resting eyes open condition; sVR: *Elements DNA* virtual rehabilitation simulation condition; sRC: rollercoaster simulation condition.

Figure 1. The tangible user interfaces and tabletop virtual environment in the (a) Bases and (b) Squiggles tasks of the *Elements DNA* virtual-reality system.

