



Move your virtual body: differences and similarities in brain activation patterns during hand movements in real world and virtual reality

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Abstract

Virtual reality (VR) is a promising tool for neurological rehabilitation, especially for motor rehabilitation. In the present study, we investigate whether brain activation patterns that are evoked by active movements are comparable when these movements are carried out in reality and in VR. Therefore, 40 healthy adults (20 men, mean age 25.31 years) performed hand movements and viewed these movements in a first-person view in reality, a VR scene showing realistic virtual hands, and a VR scene showing abstract virtual hands, in a randomized order. The VR conditions were presented via an immersive 3D head-mounted display system. EEG activity was assessed over the hand motor areas during and after movement execution. All three conditions led to typical EEG activation patterns over the motor cortex. Hence, brain activation patterns were largely comparable between conditions. However, the VR conditions, especially the abstract VR condition, led to a weaker hemispheric lateralization effect compared to the real-world condition. This indicates that hand models in VR should be realistic to be able to evoke activation patterns in the motor cortex comparable to real-world scenarios.

Keywords Brain activity · Brain lateralization · Motor task · Presence · Virtual reality

1 Introduction

Virtual realities (VR) are increasingly used not only for entertainment purposes, but also as clinical and rehabilitation tools. For instance, virtual environments can be used

to treat anxiety disorders (Meyerbröcker and Emmelkamp 2011), pain (Shahnaz Shahrbanian et al. 2012), and they are also used to support neurological rehabilitation, for instance, to restore hand and foot movements (Adamovich et al. 2009; Laver et al. 2017; Lee et al. 2019; Piron et al. 2009; Saposnik and Levin 2011; Shin et al. 2016; Sveistrup 2004). For such clinical applications, VR offers the possibility of safe training environments, which can be individually adapted to the patients' needs. VR can improve training motivation by providing engaging and interesting VR scenarios (Levin et al. 2012; Teo et al. 2016). Additionally, VR scenarios enable cost effective training at home (Adamovich et al. 2009; Putrino 2014).

In the context of motor rehabilitation, it is assumed that an adaptive and engaging VR can provide intensive sensorimotor stimulation, which is needed to induce brain reorganization (Adamovich et al. 2009; Jang et al. 2005). Neurophysiological and behavioral benefits of tasks such as movement observation, practicing or imitating movements can be easily incorporated into VR to target brain areas necessary for functional recovery (Adamovich et al. 2009). Generally, motor training in VR has similar positive effects on motor function than motor training in the real world (Karamians et al. 2020; Laver et al. 2017; Lee et al. 2019). For

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instance, kinematics of movements are similar in real and virtual environments and changes in brain activation patterns due to virtual and real motor training are largely similar in neurologic patients (Adamovich et al. 2009). There is also evidence that VR can be used to activate the mirror neuron system in the brain. Merians et al. (2009) performed a VR study, in which a stroke patient performed movements with the unaffected hand. These movements were translated to movements of a corresponding or contralateral virtual hand model in VR. Watching the movements of the virtual hand of the affected side lead to increases of activation patterns in the motor areas of the affected brain areas.

In this context, it is still an open question whether brain activation patterns that are evoked by executing and looking at one's own movements in the first-person view in reality are comparable to brain activation patterns that are evoked by executing and looking at the same movements in VR. Adamovich et al. (2009) also conclude in their review that "imaging studies to evaluate the effects of sensory manipulation on brain activation ... are needed to guide future clinical inquiry" (Adamovich et al. 2009, pp. 1). In the present study, we investigated this question by comparing EEG activation patterns over the motor cortex when watching one's own hand movements in reality and in VR.

Prior neuroscientific studies report on heterogeneous results concerning the comparability of brain activation patterns evoked by real and corresponding VR tasks (Aghajan et al. 2015; Perani et al. 2001; Romero-Soto et al. 2020; Wang et al. 2020). There is some evidence that neural firing is not directly comparable between real-world scenarios and virtual scenarios. For instance, Aghajan et al. (2015) investigated firing of cells in the hippocampus of rats, which generally fire during spatial navigation when a cognitive map of the environment is generated. They found that these cells did not fire in the same systematic way when navigating through a virtual environment compared to a real environment. Perani et al. (2001) assessed brain activation patterns while passively observing movements of real and virtual hands using fMRI. They found that watching the virtual hand movements produced significantly smaller activation in the frontoparietal circuit that was recruited when watching movements of a real hand. In contrast to the study by Perani et al. (2001), in the present study we do not use a passive watching paradigm. Instead, participants actively move their hands and watch these active movements by looking at their own hands in reality or their movements are translated to movements of virtual hand models. Pacheco et al. (2017) compared EEG activity during going up and down a step in the real world and in VR. They found differences in different EEG frequency bands (increase in theta and alpha power in real-world condition, increase in beta and gamma power in VR condition) during the execution of such a lower limb motor task according to the environment that the individual was exposed. Baumeister et al. (2010) also found differences

in different EEG frequency bands between a real-world golf putting task and a corresponding virtual task (increased theta and alpha 2 power during real putting). Wang et al. (2020) reported comparable changes in EEG power (decreasing alpha and beta power) over the sensorimotor cortex during a full-body reaching task when comparing a real-world and a VR condition. Romero-Soto et al. (2020) also found comparable EEG activity (frontal alpha synchrony) in a real-world and VR condition of the game "Power Solitaire". The heterogeneous results of these prior studies might be related to methodological differences, e.g., differences in VR systems or movement visualization (Ferreira Dos Santos et al. 2016).

Beside the comparison between real and virtual hand movements, we further distinguished between watching movements of a realistic and an abstract VR hand model. The design and visualization of the VR environment might affect the impact of a VR interaction on brain activity (Ferreira Dos Santos et al. 2016; Pyasik et al. 2020). There is some evidence from brain-computer interface (BCI) studies that realistic humanlike visual feedback can induce a sense of embodiment when imagining hand movements and consequently might optimize the activation in motor brain areas (Alimardani et al. 2018; Ono et al. 2013). Pfurtscheller et al. (2007) showed that viewing a hand moving realistically in VR led to a stronger activation of the motor cortex (as indicated by an event-related desynchronization of the central beta rhythm) than viewing a moving cube in VR. Tunik et al. (2013) showed that visuomotor discordance during visually guided hand movement in VR modulates activity in the motor areas of the brain.

In summary, here we investigate similarities and differences in activation patterns of the motor cortex when actively moving one's own hands and watching these active movements in reality compared to a 3D highly immersive VR condition using a head-mounted display. We also differentiate between two VR conditions: in one VR condition, actual hand movements were translated to movements of a realistic virtual hand model while in the other VR condition, actual hand movements were translated to movements of an abstract virtual hand model. Looking at realistic virtual hand models could activate motor brain areas in a more similar way to viewing one's own hands in reality during movement execution, for instance by additionally activating the mirror neuron system or inducing a sense of embodiment, compared to the abstract VR condition (Alimardani et al. 2018; Merians et al. 2009; Pfurtscheller et al. 2007).

2 Material and methods

2.1 Participants

Forty healthy adults participated in the present study (mean age 25.31 years, SD = 5.09; 20 male participants). All

participants were right-handed, which was assessed with the Edinburgh Handedness Inventory (EHI, Oldfield 1971). Participants reached a mean score of 85.48 (SD=20.18) in the EHI. In the EHI, values can range from -100 (very strong left-hander) to 100 (very strong right-hander). All volunteers gave written informed consent. The study was approved by the local ethics committee of the University of Graz, Austria (GZ. 39/55/63 ex 2018/19) and is in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans (WMA (World Medical Association) 2009).

2.2 Procedure

All participants performed all experimental conditions in a pseudo-randomized order (matching for gender). After signing the informed consent and receiving written instructions explaining the procedure, demographic data and handedness (EHI) were assessed as well as a baseline measurement of cybersickness using the Simulator Sickness Questionnaire (SSQ; Kennedy et al. 1993). This questionnaire assesses symptoms that can occur during or after interactions with VR systems, encompassing nausea, disorientation, and oculomotor symptoms. Moreover, one further questionnaire (KUT, Kontrollueberzeugung im Umgang mit Technik, i.e., control beliefs while dealing with technology Beier 1999) was completed for exploratory purpose with no further relevance for the present study. Then, the EEG electrodes were mounted on the participants' heads. Before each experimental condition, participants performed EEG resting measurements with open and closed eyes (1 min each, in the VR conditions the VR headset was already mounted on the participants' heads) and they performed a motor task in which they should stack wooden blocks (either in VR or real world, Fig. 1) to familiarize with the virtual hands (duration of about 2 min). After stacking wooden blocks, participants were asked to rate how much they had the feeling that the movements of the virtual hands matched those of their own hands on a visual analogue scale (VAS) ranging from 0 ("not at all") to 100 ("perfect match). After that, the corresponding experimental condition started.

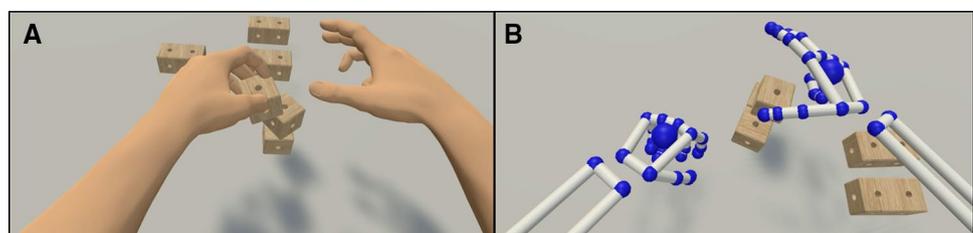
Three experimental conditions were performed in which participants were instructed to actively open and close either their right or left hand (making a fist) in an approximately

one-second-pace. This movement was practiced before the start of the measurement. During the experimental conditions, participants were sitting and could comfortably put their elbows on the arm rest of the chair. In all three experimental conditions, participants viewed their own hands in a first-person view. In the real-world condition, they saw their own hands. In the realistic VR condition, they wore the VR headset and their actual movements were translated to the movements of realistic hand models (Fig. 1a). In the abstract VR condition, they wore the VR headset and their actual movements were translated to the movements of abstract hand models (Fig. 1b).

The timing of each of the movement tasks was as follows (Fig. 2): An auditory cue (beep tone) was presented to indicate that the movement task instruction will follow soon. One second later, the auditory command "left hand" or "right hand" followed indicating that participants should start moving their hand (opening and closing it in a 1-s-pace), respectively. The duration of the motor task was 5 s. Participants heard "Stop" after these 5 s, indicating that they should stop the movement. Afterward, a variable pause (2.5–4.5 s) followed in which participants should relax and not move. Then, the next trial started with the auditory cue (beep tone). This timing of the trials is in accordance with prior EEG studies investigating cortical correlates of hand movements (Pfurtscheller and Lopes da Silva 1999; Pfurtscheller and Neuper 1997). In sum, 20 right hand movement trials and 20 left hand movement trials were performed for each experimental condition. Participants saw the virtual hands continuously also during the pause interval. They were instructed to avoid strong movements (e.g., head movements) during the whole EEG measurement to prevent excessive movement artifacts.

After each VR condition, participants filled out the Short Feedback Questionnaire (SFQ, Kizony et al. 2006) to assess the level of presence in the VR conditions. The SFQ is a short post-immersive presence questionnaire containing only six questions related to the feeling of presence, i.e., the participant's feeling of enjoyment, sense of being in the environment, feeling of success, feeling of control, perception of the environment as being realistic, and whether the feedback from the computer was understandable or not. The items of the SFQ are assessed on a five-point Likert scale, ranging from 1 (not at all) to 5

Fig. 1 VR hand models. Example views of **a** the realistic and **b** abstract virtual hands during the block stacking task



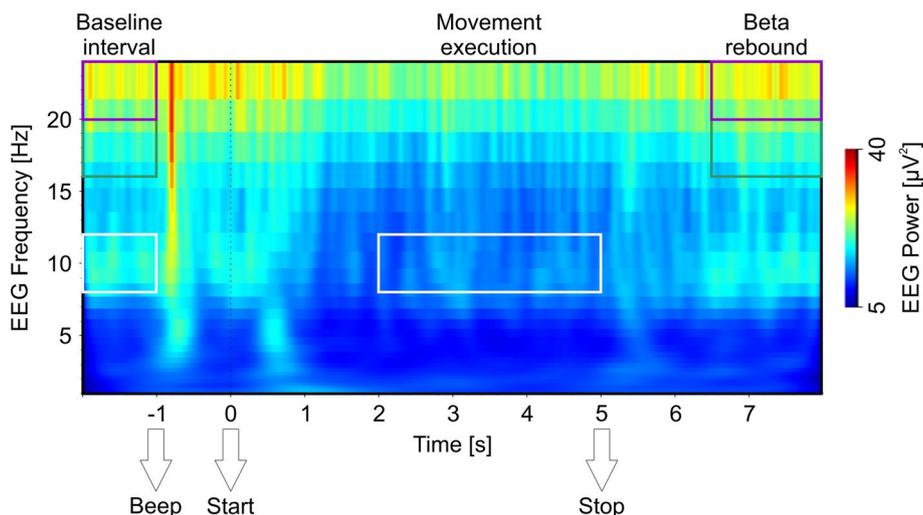


Fig. 2 EEG time–frequency map. Example of an EEG time–frequency map (wavelet analysis) for a left hand movement over the right hemisphere during the real-world condition. The arrows indicate the timing of the movement execution task (beep tone, start and stop of movement execution). White rectangles indicate the EEG frequency range of mu (8–12 Hz), green rectangles of beta 1 (16–20 Hz), and purple rectangles of beta 2 (20–24 Hz). The time inter-

val one second before the beep tone was used as baseline interval for ERD/ERS calculations. As one can see, mu power decreases from baseline to the task interval (movement execution, s 2–5) reflecting an ERD in the mu frequency range. Beta 1 and beta 2 power increase from the baseline interval to the pause interval after movement execution (beta rebound, 1.5–3 s after stopping the movement) reflecting an ERS in the beta frequency ranges

(a lot). The internal consistency reliability (Cronbach’s alpha) ranges between $\alpha = 0.70$ to $\alpha = 0.81$ (Kizony et al. 2006). At the end of the measurement, participants filled out the SSQ again to reveal possible changes in sickness symptoms during the course of the measurement. The whole experiment lasted approximately for one hour.

2.3 VR equipment

For the presentation of the VR conditions, a head-mounted display (HMD; HTC Vive Pro) with a resolution of 2880×1600 pixels (1440×1600 pixels per eye) and a refresh rate of 90 Hz was used. This is an immersive 3D VR system widely used in the gaming industry. It enables the stereoscopic presentation of a VR in 360 degrees from the egocentric perspective using modern tracking technology to accurately determine the position of the HMD.

To track the actual hand movements of the participants and to translate the real hand movements into movements of the virtual hands, the Leap Motion Controller was used. This is an optical hand tracking module that captures the movements of hands with high accuracy. The Leap Motion Controller was mounted on the VR HMD. The virtual hand models (realistic and abstract model, Fig. 1) were from example applications of the Leap Motion system and designed and presented with the game engine Unity (Unity Technologies, San Francisco, CA).

2.4 EEG data recording and analysis

EEG data were recorded by eight Ag/AgCl passive electrodes over FC3, FC4, C3, C1, C2, C4, CP3, and CP4 according to the extended 10–20 electrode placement system. Note that for data analysis only C3 (motor hand area over left hemisphere) and C4 (motor hand area over right hemisphere) were used. For data recording, a g.USBamp 16 channels standard amplifier (g.tec, Graz, Austria) was used with a sampling rate of 256 Hz. The ground was placed at Fz. Data was referenced to linked mastoids. Additionally, vertical and horizontal eye movements (electrooculogram, EOG) were recorded with three electrodes in total, two were placed on the outer canthi of the eyes and one was placed superior to the nasion. Electrode impedances were kept below 10 kOhms.

EEG data preprocessing and analysis were performed with the Brain Vision Analyzer software (version 2.01, Brain Products GmbH, Munich, Germany). Data were filtered using a 0.5 Hz high-pass filter, a 70 Hz low-pass filter and a 50 Hz Notch filter. Ocular artifacts such as eye blinks were automatically removed using Independent Component Analysis (ICA). After ocular artifact correction, a semi-automated rejection of other EEG artifacts (e.g., muscles) was performed (Criteria for rejection: $> 50.00 \mu\text{V}$ voltage step per sampling point, absolute voltage value $> \pm 150.00 \mu\text{V}$, lowest allowed activity in 100 ms intervals: $0.5 \mu\text{V}$). All epochs with artifacts were excluded from the EEG analysis.

To analyze changes in motor brain activity during the hand movement tasks, we calculated the event-related desynchronisation/synchronisation (ERD/ERS) in different EEG frequency bands (Pfurtscheller 1989; Pfurtscheller and Lopes da Silva 1999). ERD/ERS values are a measure of the percentage change in EEG band power between the baseline interval (one second before the auditory cue/beep tone) and a task interval (e.g., during movement execution). To avoid that ERD/ERS is influenced by phase-locked EEG activities, which include all types of event-related potentials (ERPs), the ERD/ERS calculation was based on the intertrial variance method. Therefore, all trials were bandpass filtered in the analyzed frequency bands. Then, the average of these filtered trials was calculated and in a following step subtracted from each data point separately, warranting that only non-phase-locked activity was quantified. Finally, data were squared to get band power values and averaged over trials (Kalcher and Pfurtscheller 1995). For calculating ERD/ERS values, the following formula was used: $ERD/ERS = [(band\ power\ task - band\ power\ baseline) / (band\ power\ baseline)] \times 100$. Note that negative values are associated with an ERD (relative decrease in band power from baseline to task interval) and positive values with an ERS (relative increase in band power from baseline to task interval).

We analyzed ERD/ERS values in three different frequency bands over C3 and C4: mu (8–12 Hz), beta 1 (16–20 Hz), and beta 2 (20–24 Hz). Generally, during motor execution there is a relative decrease in mu activity (ERD) compared to the baseline interval (Pfurtscheller and Lopes da Silva 1999). Therefore, we analyzed mu ERD during movement execution (task interval starting 2 s after movement onset till the end of the movement, duration of 3 s). Hand movements should lead to a more bilateral activation (ERD in the mu rhythm) over the hand motor areas (C3 and C4) (McFarland et al. 2000; Neuper et al. 2006; Pfurtscheller 1989). Directly after the movement, a prominent phenomenon in the EEG is the so-called beta rebound or post-movement beta ERS (Neuper et al. 2006; Pfurtscheller et al. 1996; Pfurtscheller and Lopes da Silva 1999). This is a relative increase in beta activity (ERS) compared to the baseline interval directly after movement execution. It is interpreted to reflect a short-lasting state of deactivation or inhibition of motor cortex networks (Neuper et al. 2006; Pfurtscheller et al. 1996; Pfurtscheller and Lopes da Silva 1999). Therefore, we analyzed the ERS in the beta 1 and beta 2 frequency range after movement execution (task interval starting 1.5 s after stopping the movement, duration of 1.5 s). The beta rebound (ERS in beta 1 and beta 2) should be more laterally pronounced, i.e., right hand movements should lead to a stronger beta ERS over the left motor cortex (C3) and left hand movements should lead to a stronger beta ERS over the right motor cortex (C4) (Pfurtscheller et al. 1996; Salmelin and Hari 1994). Figure 2 illustrates an example of an EEG

time–frequency map indicating the time intervals and frequency ranges used for ERD/ERS analysis.

2.5 Statistical analysis

To compare presence values and other subjective experiences between the realistic and abstract VR condition, we used paired-samples *t*-tests. To investigate differences in EEG activity, we calculated ANOVAs with the within subject factors experimental condition (real-world vs. realistic VR vs. abstract VR), hand (left vs. right hand movement), and hemisphere (left vs. right motor cortex) separately for mu ERD, beta 1 ERS, and beta 2 ERS. Additionally, we performed exploratory post-hoc paired-samples *t*-tests to reveal lateralization effects by comparing EEG activity between the left (C3) and right (C4) hemisphere separately for each EEG frequency band and experimental condition. The level for a type I error was set to 5% and post-tests were Bonferroni–Holm corrected.

3 Results

3.1 Presence experience and simulator sickness

The presence experience was stronger in the realistic VR condition ($M = 3.46$, $SE = 0.09$) compared to the abstract VR condition ($M = 3.27$, $SE = 0.09$) [$t(39) = 2.24$, $p < 0.05$].

Participants reported that they felt that the movements of the virtual hands largely corresponded to those of their own hands using a VAS ranging from 0 (“not at all”) to 100 (“perfect match”). This subjective match between the virtual and real hand movements did not differ between the realistic ($M = 72.60$, $SE = 2.10$) and abstract VR condition ($M = 70.47$, $SE = 2.64$) [$t(39) = 0.95$, $p = 0.35$].

When comparing the SSQ total score assessed at the beginning and the end of the whole measurement, sickness symptoms were overall stronger (total score) at the end of the measurement than during the baseline at the beginning of the measurement. When having a closer look at the single subscales, especially oculomotor problems (e.g., eyestrain) increased during the measurement as well as disorientation (e.g., dizziness). Table 1 summarizes results of the subscales and the total score of the SSQ assessed before and after the whole measurement.

3.2 EEG results

3.2.1 Mu ERD during motor execution

An ANOVA model with the within subject factors experimental condition (real-world vs. realistic VR vs. abstract VR), hand (left vs. right hand movement), and hemisphere

Table 1 Results of the SSQ

	Before the measurement	After the measurement	Results of <i>t</i> -tests
	Mean (SE)	Mean (SE)	<i>t</i> (<i>df</i>), <i>p</i> -values
Nausea	12.16 (1.96)	9.06 (1.71)	1.53 (39), 0.14
Oculomotor problems	11.75 (1.80)	24.07 (2.78)	-4.96 (39), <0.001*
Disorientation	4.87 (1.28)	10.79 (2.71)	-2.60 (39), 0.013*
Total score	10.00 (1.22)	14.59 (1.71)	-3.26 (39) 0.002*

Means and SE of SSQ subscales and total scale assessed before and after the whole measurement and the results of the statistical comparison (paired sample *t*-tests)

*Significant results after Bonferroni–Holm correction

(left vs. right motor cortex) revealed no significant effects. Exploratory post-hoc *t*-tests also revealed no significant differences in mu ERD between the left and right hemisphere in none of the conditions after Bonferroni–Holm correction. This indicates a bilateral activation pattern during right and left hand movements in all three experimental conditions. Figure 3 illustrates mu ERD of all conditions.

3.2.2 Beta 1 ERS after motor execution

An ANOVA model with the within subject factors experimental condition (real-world vs. realistic VR vs. abstract VR), hand (left vs. right hand movement), and hemisphere (left vs. right motor cortex) revealed a significant interaction effect hand*hemi [$F(1,37) = 17.55, p < 0.001, \eta^2 = 0.32$]. A left hand movement led to a stronger response (beta 1 ERS) over the right motor cortex while a right hand movement led to a stronger response (beta 1 ERS) over the left motor cortex. The three-way interaction effect condition*hand*hemi was not significant [$F(2,74) = 0.99, p = 0.38, \eta^2 = 0.03$] indicating a comparable hemispheric lateralization effect in all three conditions. However, exploratory post-hoc *t*-tests showed that in the real-world condition, a left hand movement led to a stronger response over the right motor cortex [$t(39) = -3.27, p < 0.01$] while a right hand movement led to a stronger response over the left motor cortex [$t(39) = 3.40, p < 0.01$]. In the realistic VR condition, a left hand movement also led to a stronger response over the right motor cortex [$t(37) = -2.53, p < 0.05$] while a right hand

movement did not lead to a statistically significant stronger response over the left motor cortex [$t(37) = 2.00, p = 0.05$]. Note that in the realistic VR condition 2 participants had to be excluded because of problems with the EEG recording during this condition. In the abstract VR condition, a left hand movement did not lead to a stronger response over the right motor cortex [$t(39) = -1.33, p = 0.19$] while a right hand movement led to a stronger response over the left motor cortex [$t(39) = 4.36, p < 0.001$]. Figure 4 illustrates beta 1 ERS for all conditions.

3.2.3 Beta 2 ERS after motor execution

An ANOVA model with the within subject factors experimental condition (real-world vs. realistic VR vs. abstract VR), hand (left vs. right hand movement), and hemisphere (left vs. right motor cortex) revealed a significant interaction effect hand*hemi [$F(1,37) = 18.12, p < 0.001, \eta^2 = 0.33$]. A left hand movement led to a stronger response (beta 2 ERS) of the right motor cortex while a right hand movement led to a stronger response (beta 2 ERS) of the left motor cortex. The three-way interaction effect condition*hand*hemi was not significant [$F(2,74) = 1.59, p = 0.21, \eta^2 = 0.04$], indicating a comparable hemispheric lateralization effect in all three conditions. Exploratory post-hoc *t*-tests showed that in the real-world condition, a left hand movement led to a stronger response over the right motor cortex [$t(39) = -2.99, p < 0.01$] while a right hand movement led to a stronger response over the left motor cortex [$t(39) = 3.74, p < 0.001$].

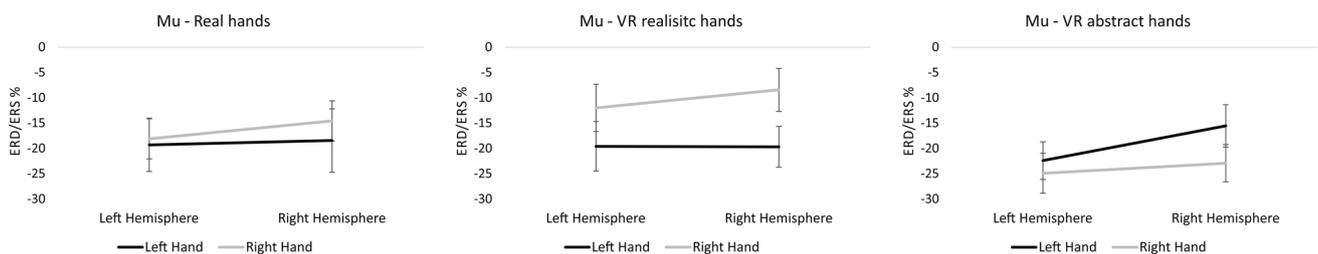


Fig. 3 Mu ERD during motor execution. Means and SE of mu ERD presented separately for the 3 experimental conditions, the left (C3) and right (C4) hemisphere, and the left and right hand movement. Note that negative values indicate ERD values

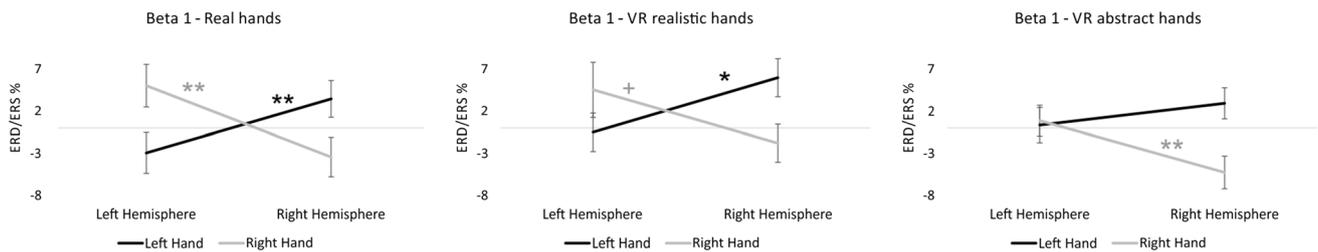


Fig. 4 Beta 1 ERS after motor execution. Means and *SE* of beta 1 ERS presented separately for the 3 experimental conditions, the left (C3) and right (C4) hemisphere, and the left and right hand move-

ment. Note that positive values indicate ERS values. Asterisks indicate significant results of *t*-tests comparing left and right hemisphere (** $p < 0.01$, * $p < 0.05$, + $p = 0.05$)

In the realistic VR condition, a left hand movement also led to a stronger response over the right motor cortex [$t(37) = -3.27$, $p < 0.01$] while a right hand movement did not lead to a statistically significant stronger response over the left motor cortex [$t(37) = 1.97$, $p = 0.05$]. Note that in the realistic VR condition 2 participants had to be excluded because of problems with the EEG recording during this condition. In the abstract VR condition, a left hand movement did not lead to a stronger response over the right motor cortex [$t(39) = -1.48$, $p = 0.15$] while a right hand movement led to a stronger response over the left motor cortex [$t(39) = 2.84$, $p < 0.01$]. Figure 5 illustrates beta 2 ERS for all conditions.

4 Discussion

In the present study, we compared activation patterns over the motor cortex while actively moving either the right or left hand between three different conditions: a real-world condition, a realistic VR condition, and an abstract VR condition. Generally, typical activation patterns (bilateral mu ERD and lateralized beta ERS) were observed in all three conditions. However, lateralization effects were not so strongly pronounced in the VR conditions, especially in the abstract VR condition, as will be outlined in more detail below.

All three conditions led to typical changes in EEG activity recorded over the motor cortex when performing hand movements and viewing these movements in a first-person view. In the real-world condition as well as in both VR conditions, a bilateral ERD in the mu rhythm was observed during motor task execution. This is in line with prior real-world and VR studies that also found a more bilaterally distributed mu ERD when performing and / or watching hand movements (McFarland et al. 2000; Neuper et al. 2006; Pfurtscheller 1989; Pfurtscheller et al. 2007; Pfurtscheller and Lopes da Silva 1999). Additionally, in all three conditions the prominent beta rebound or post-movement beta ERS was observed, especially in the contralateral motor area (Neuper et al. 2006; Pfurtscheller et al. 1996; Pfurtscheller and Lopes da Silva 1999; Salmelin and Hari 1994). Hence, hand movements in VR led to comparable activation patterns in motor brain areas compared to a real-world condition. This is in line with a prior VR study comparing changes in EEG activity over the sensorimotor cortex during a full-body reaching task between a real-world and a VR condition (Wang et al. 2020). As in the present study, Wang et al. (2020) used a 3D fully immersive head-mounted display VR system to present the virtual body. Studies that found larger differences in brain activation patterns evoked in real-world and corresponding VR motor tasks used different VR equipment. Pacheco et al. (2017), Oliveira et al. (2018), as well as Baumeister et al. (2010) used the Nintendo Wii to present

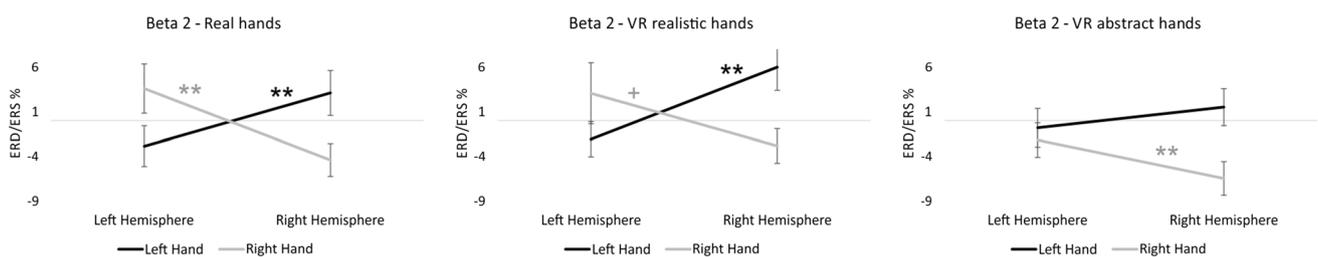


Fig. 5 Beta 2 ERS after motor execution. Means and *SE* of beta 2 ERS presented separately for the 3 experimental conditions, the left (C3) and right (C4) hemisphere, and the left and right hand move-

ment. Note that positive values indicate ERS values. Asterisks indicate significant results of *t*-tests comparing left and right hemisphere (** $p < 0.01$, * $p < 0.05$, + $p = 0.05$)

the VR motor task conditions (going up and down a step and golf putting, respectively). The Nintendo Wii presents the VR environment on a conventional computer screen or TV. There is evidence that the degree of immersion allowed by VR systems can lead to differences in brain activation patterns. A highly immersive 3D VR system can generally lead to stronger brain activation patterns than a less immersive 2D VR system (Kober et al. 2012). Probably, the less immersive Nintendo Wii VR conditions might have led to differences in brain activation patterns between real-world and VR conditions, while a highly immersive 3D VR condition using an HMD VR system leads to more comparable brain activation patterns.

While all conditions led to a mu ERD and a beta ERS, exploratory analyses of hemispheric lateralization effects revealed differences between the real-world and VR conditions. Since the analysis of beta 1 and beta 2 ERS revealed the same effects, we will refer to beta ERS summarizing the effects of both beta frequency bands. In the real-world condition, after stopping the hand movement, a lateralized beta ERS was observed, i.e., a right hand movement led to a stronger beta ERS over the left motor cortex while a left hand movement led to a stronger beta ERS over the right motor cortex, which is in line with prior findings (Pfurtscheller et al. 1996; Salmelin and Hari 1994). In the realistic VR condition, where one's own hand movements were translated to movements of a realistic VR hand model, moving the left hand led to a stronger beta ERS over the right motor cortex after stopping the movement comparably to the results of the real-world condition. This lateralized beta rebound was not as strongly pronounced after stopping a right hand movement. A right hand movement led to a numerically higher beta ERS over the left motor cortex, but this difference was only significant by trend ($p=0.05$). In the abstract VR condition, in which one's own hand movements were translated to movements of an abstract VR hand model, the lateralized beta rebound effect was only observed after stopping a right hand movement (led to a significant stronger beta ERS over the left motor cortex), but not after a left hand movement (no difference in beta ERS between the left and right motor cortex). Hence, the lateralized beta rebound was quite similar in the real-world and realistic VR condition while it differed more strongly between the real-world and abstract VR condition (Figs. 4, 5).

The reasons why brain activation patterns evoked by the real-world condition and the realistic VR condition were more similar than brain activation patterns evoked by the real-world condition and the abstract VR condition might be related to the presence experience and embodiment. The realistic VR condition led to a stronger “sense of being there”, also known as presence experience, than the abstract VR condition. A heightened sense of presence in VR should enhance the user's capacity for interaction with

the virtual simulation. Additionally, an increased presence experience should foster natural behavior in VR and increase the chance of transfer effects to real-world behavior (Cummings and Bailenson 2016; Grassini and Laumann 2020; Kober et al. 2012; Slater et al. 1996). This might also lead to similar brain activation patterns than in real-world conditions. Maselli and Slater (2013) showed that the subjective feeling as well as corresponding physiological reactions of body ownership in VR were stronger when the virtual body has a realistic skin tone compared to an unrealistic looking virtual body. A stronger feeling of body ownership in the realistic compared to the abstract VR condition might explain differences in brain activation patterns as well. BCI studies also show that realistic humanlike visual feedback leads to a stronger embodiment when imagining hand movements than more abstract feedback (Alimardani et al. 2018; Ono et al. 2013). Watching the realistic virtual hands in the present study might have resembled a self-body action leading to similar brain activation patterns than watching one's own real hands (Alimardani et al. 2018). Accordingly, convergent evidence is observed also when using the virtual hand illusion paradigm. Pyasik et al. (2020) used more or less realistic versions of a virtual hand to investigate the determinants of embodiment in the virtual hand illusion and observed that the visual appearance of a virtual hand affects embodiment. Their results suggest that the detailed appearance of the body might act as an additional component in the construction of body ownership. Moreover, Matamala-Gomez et al. (2020) observed that the degree of distortion of a virtual hand in comparison to the real limb determined the intensity of pain as indicated by several physiological measurements. Together, these results suggest that a virtual hand containing a larger number of features common also to the real hand is more effective eliciting (electro-)physiological as well as cognitive responses typical of real hand perception and movement.

4.1 Limitations

In the present study, we investigated healthy individuals. Effects of real-world and different VR scenarios on brain activation patterns during executing motor tasks in neurologic patients have to be investigated in the future.

Participants did not wear the HMD VR system during the real-world condition. However, brain activation patterns were largely comparable between the real-world and VR conditions. Additionally, prior studies showed that wearing a VR headset generally does not negatively affect the baseline EEG. Wang et al. (2020) investigated the impact of a 3D fully immersive HMD VR system on the integrity of EEG data. They found no differences in resting EEG data between a condition with and without the VR headset.

Over the course of the whole measurement, simulator sickness symptoms as assessed with the SSQ increased, especially oculomotor problems and disorientation. However, we did not assess simulator sickness after each condition, so we cannot say if this increase in sickness symptoms is an unspecific effect or related to a specific experimental condition.

In the present study, all participants were right-handed. It is well known from imaging studies that activation of motor areas during hand movements differs between right- and left-handed individuals. For instance, left-handers activate a larger number of brain areas than right-handers. Additionally, left-handers show significantly less brain lateralization when performing complex motor tasks but there are no such differences for simple movement tasks (Solodkin et al. 2001). In the present study, we used a relatively simple movement task (opening and closing the hand). Hence, handedness might not have such a strong effect on our results. However, future studies might also address the question of handedness when comparing brain activation patterns in motor areas elicited by real and virtual hand movements.

4.2 Conclusions

Here, we show that motor brain activation patterns evoked by real and virtual hand movements are largely comparable when using an immersive 3D HMD VR system. This indicates that immersive VR scenarios might be potentially useful to restore specific activation in affected motor brain areas in patients with neurological pathologies. Our results also show that using realistic hand models in VR is advisable to evoke comparable lateralized activation patterns in motor brain areas than in real-world scenarios.

Author contributions All authors were involved in designing the research and conceptualization; S.E.K. and M.B. performed the research; S.E.K., V.S., U.A., and G.W. contributed resources, software, and/or analytic tools; S.E.K. and M.B. performed data analysis and interpretation; S.E.K. wrote the original draft; all authors reviewed, edited, and approved the manuscript.

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Data availability Data that support the findings of this study are available on request from the corresponding author (S.E.K.) after contacting the Ethics Committee of the University of Graz (ethikkommission@uni-graz.at) for researchers who meet the criteria for access to confidential data. These ethical restrictions prohibit the authors from making the data set publicly available.

Declarations

Conflict of interests The authors declare that they have no conflict of interest.

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References

- Adamovich SV, Fluet GG, Tunik E, Merians AS (2009) Sensorimotor training in virtual reality: a review. *NeuroRehabilitation* 25:29–44
- Aghajan ZM, Acharya L, Moore JJ, Cushman JD, Vuong C, Mehta MR (2015) Impaired spatial selectivity and intact phase precession in two-dimensional virtual reality. *Nat Neurosci* 18:121–128. <https://doi.org/10.1038/nn.3884>
- Alimardani M, Nishio S, Ishiguro H (2018) Brain–computer interface and motor imagery training: the role of visual feedback and embodiment. *Evol BCI Ther Engaging Brain State Dyna* 2:64
- Baumeister J, Reinecke K, Cordes M, Lerch C, Weiss M (2010) Brain activity in goal-directed movements in a real compared to a virtual environment using the Nintendo Wii. *Neurosci Lett* 481:47–50. <https://doi.org/10.1016/j.neulet.2010.06.051>
- Beier G (1999) Kontrollüberzeugungen im Umgang mit Technik. *Rep Psychol* 9:684–693
- Cummings JJ, Bailenson JN (2016) How immersive is enough? a meta-analysis of the effect of immersive technology on user presence. *Media Psychol* 19:272–309. <https://doi.org/10.1080/15213269.2015.1015740>
- de Oliveira SMS, de Medeiros CSP, Pacheco TBF, Bessa NPOS, Silva FGM, Tavares NSA, Rego IAO, Campos TF, Cavalcanti FAdC (2018) Electroencephalographic changes using virtual reality program: technical note. *Neurol Res* 40:160–165. <https://doi.org/10.1080/01616412.2017.1420584>
- Ferreira Dos Santos L, Christ O, Mate K, Schmidt H, Krüger J, Dohle C (2016) Movement visualisation in virtual reality rehabilitation of the lower limb: a systematic review. *Biomed Eng Online* 15:144. <https://doi.org/10.1186/s12938-016-0289-4>
- Grassini S, Laumann K (2020) Questionnaire measures and physiological correlates of presence: a systematic review. *Front Psychol* 11:349. <https://doi.org/10.3389/fpsyg.2020.00349>
- Jang SH, You SH, Hallett M, Cho YW, Park C-M, Cho S-H, Lee H-Y, Kim T-H (2005) Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study. *Arch Phys Med Rehabil* 86:2218–2223. <https://doi.org/10.1016/j.apmr.2005.04.015>
- Kalcher J, Pfurtscheller G (1995) Discrimination between phase-locked and non-phase-locked event-related EEG activity. *Electroencephalogr Clin Neurophysiol* 94:381–384
- Karamians R, Proffitt R, Kline D, Gauthier LV (2020) Effectiveness of virtual reality- and gaming-based interventions for upper extremity rehabilitation poststroke: a meta-analysis. *Arch Phys Med Rehabil* 101:885–896. <https://doi.org/10.1016/j.apmr.2019.10.195>
- Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *Int J Aviat Psychol* 3:203–220

- Kizony R, Katz N, Rand D, Weiss PL (2006) A Short Feedback Questionnaire (SFQ) to enhance client-centered participation in virtual environments. In: Proceedings of 11th annual Cybertherapy conference. Virtual Healing: Designing Reality
- Kober SE, Kurzmann J, Neuper C (2012) Cortical correlate of spatial presence in 2D and 3D interactive virtual reality: an EEG study. *Int J Psychophysiol* 83:365–374
- Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M (2017) Virtual reality for stroke rehabilitation. *Cochrane Database Syst Rev* 11:CD008349. <https://doi.org/10.1002/14651858.CD008349.pub4>
- Lee HS, Park YJ, Park SW (2019) The effects of virtual reality training on function in chronic stroke patients: a systematic review and meta-analysis. *Biomed Res Int* 2019:7595639. <https://doi.org/10.1155/2019/7595639>
- Levin MF, Snir O, Liebermann DG, Weingarden H, Weiss PL (2012) Virtual reality versus conventional treatment of reaching ability in chronic stroke: clinical feasibility study. *Neurol Ther* 1:3. <https://doi.org/10.1007/s40120-012-0003-9>
- Maselli A, Slater M (2013) The building blocks of the full body ownership illusion. *Front Hum Neurosci* 7:83. <https://doi.org/10.3389/fnhum.2013.00083>
- Matamala-Gomez M, Nierula B, Donegan T, Slater M, Sanchez-Vives MV (2020) Manipulating the perceived shape and color of a virtual limb can modulate pain responses. *J Clin Med* 9:291
- McFarland DJ, Miner LA, Vaughan TM, Wolpaw JR (2000) Mu and beta rhythm topographies during motor imagery and actual movements. *Brain Topogr* 12:177–186. <https://doi.org/10.1023/A:1023437823106>
- Merians AS, Tunik E, Adamovich SV (2009) Virtual reality to maximize function for hand and arm rehabilitation: exploration of neural mechanisms. *Stud Health Technol Inform* 145:109–125
- Meyerbröker K, Emmelkamp PMG (2011) Virtual reality exposure therapy for anxiety disorders: the state of the art. In: Brahmam S, Jain LC (eds) *Advanced computational intelligence paradigms in healthcare 6*. Virtual reality in psychotherapy, rehabilitation, and assessment. Springer, Berlin, pp 47–62
- Neuper C, Wörtz M, Pfurtscheller G (2006) ERD/ERS patterns reflecting sensorimotor activation and deactivation. In: Neuper C, Klimesch W (eds) *Progress in brain research: event-related dynamics of brain oscillations*, vol 159. Elsevier, Amsterdam, pp 211–222
- Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9:97–113
- Ono T, Kimura A, Ushiba J (2013) Daily training with realistic visual feedback improves reproducibility of event-related desynchronization following hand motor imagery. *Clin Neurophysiol* 124:1779–1786. <https://doi.org/10.1016/j.clinph.2013.03.006>
- Pacheco TBF, Oliveira Rego IA, Campos TF, Cavalcanti FAdC (2017) Brain activity during a lower limb functional task in a real and virtual environment: a comparative study. *NeuroRehabilitation* 40:391–400. <https://doi.org/10.3233/NRE-161426>
- Perani D, Fazio F, Borghese NA, Tettamanti M, Ferrari S, Decety J, Gilardi MC (2001) Different brain correlates for watching real and virtual hand actions. *Neuroimage* 14:749–758. <https://doi.org/10.1006/nimg.2001.0872>
- Pfurtscheller G (1989) Spatiotemporal analysis of alpha frequency components with the ERD technique. *Brain Topogr* 2:3–8
- Pfurtscheller G, Lopes da Silva FH (1999) Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clin Neurophysiol* 110:1842–1857
- Pfurtscheller G, Stancák A, Neuper C (1996) Post-movement beta synchronization. A correlate of an idling motor area? *Electroencephalogr Clin Neurophysiol* 98:281–293. [https://doi.org/10.1016/0013-4694\(95\)00258-8](https://doi.org/10.1016/0013-4694(95)00258-8)
- Pfurtscheller G, Neuper C (1997) Motor imagery activates primary sensorimotor area in humans. *Neurosci Lett* 239:65–68. [https://doi.org/10.1016/S0304-3940\(97\)00889-6](https://doi.org/10.1016/S0304-3940(97)00889-6)
- Pfurtscheller G, Scherer R, Leeb R, Keinrath C, Neuper C, Lee F, Bischof H (2007) Viewing moving objects in virtual reality can change the dynamics of sensorimotor EEG rhythms. *Presence Teleop Virtual Environ* 16:111–118. <https://doi.org/10.1162/pres.16.1.111>
- Piron L, Turolla A, Agostini M, Zucconi C, Cortese F, Zampolini M, Zannini M, Dam M, Ventura L, Battauz M, Tonin P (2009) Exercises for paretic upper limb after stroke: a combined virtual-reality and telemedicine approach. *J Rehabil Med* 41:1016–1102. <https://doi.org/10.2340/16501977-0459>
- Putrino D (2014) Telerehabilitation and emerging virtual reality approaches to stroke rehabilitation. *Curr Opin Neurol* 27:631–636. <https://doi.org/10.1097/WCO.0000000000000152>
- Pyasik M, Tieri G, Pia L (2020) Visual appearance of the virtual hand affects embodiment in the virtual hand illusion. *Sci Rep* 10:5412. <https://doi.org/10.1038/s41598-020-62394-0>
- Romero-Soto FO, Ibarra-Zárate DI, Alonso-Valerdi LM (2020) Comparative analysis of alpha power spectral density in real and virtual environments. In: González Díaz CA, Chapa González C, Laciari Leber E (eds) *VIII Latin American conference on biomedical engineering and XLII national conference on biomedical engineering: proceedings of CLAIB-CNIB 2019*, October 2–5, 2019, Cancún, México, 1st edn. Springer, Cham, pp 156–163
- Salmelin R, Hari R (1994) Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement. *Neuroscience* 60:537–550. [https://doi.org/10.1016/0306-4522\(94\)90263-1](https://doi.org/10.1016/0306-4522(94)90263-1)
- Saposnik G, Levin M (2011) Virtual reality in stroke rehabilitation: a meta-analysis and implications for clinicians. *Stroke* 42:1380–1386. <https://doi.org/10.1161/STROKEAHA.110.605451>
- Shahrbani S, Ma X, Aghaei N, Korner-Bitensky N, Moshiri K, Simmonds M (2012) Use of virtual reality (immersive vs. non-immersive) for pain management in children and adults: a systematic review of evidence from randomized controlled trials. [https://www.semanticscholar.org/paper/Use-of-virtual-reality-\(immersive-vs.-non-for-pain-Shahrbani-Ma/2243177916644b0c509d94c59eac9cecf5fd7db](https://www.semanticscholar.org/paper/Use-of-virtual-reality-(immersive-vs.-non-for-pain-Shahrbani-Ma/2243177916644b0c509d94c59eac9cecf5fd7db)
- Shin J-H, Kim M-Y, Lee J-Y, Jeon Y-J, Kim S, Lee S, Seo B, Choi Y (2016) Effects of virtual reality-based rehabilitation on distal upper extremity function and health-related quality of life: a single-blinded, randomized controlled trial. *J NeuroEng Rehabil* 13:17. <https://doi.org/10.1186/s12984-016-0125-x>
- Slater M, Linakis V, Usoh M, Kooper R (1996) Immersion, presence, and performance in virtual environments: an experiment with tri-dimensional chess. *ACM Virtual Real softw Technol (VRST)*:163–172
- Solodkin A, Hlustik P, Noll DC, Small SL (2001) Lateralization of motor circuits and handedness during finger movements. *Eur J Neurol* 8:425–434. <https://doi.org/10.1046/j.1468-1331.2001.00242.x>
- Sveistrup H (2004) Motor rehabilitation using virtual reality. *J Neuroeng Rehabil* 1:10. <https://doi.org/10.1186/1743-0003-1-10>
- Teo W-P, Muthalib M, Yamin S, Hendy AM, Bramstedt K, Kotsoopoulos E, Perrey S, Ayaz H (2016) Does a combination of virtual reality, neuromodulation and neuroimaging provide a comprehensive platform for neurorehabilitation? A narrative review of the literature. *Front Hum Neurosci* 10:284. <https://doi.org/10.3389/fnhum.2016.00284>
- Tunik E, Saleh S, Adamovich SV (2013) Visuomotor discordance during visually-guided hand movement in virtual reality modulates sensorimotor cortical activity in healthy and hemiparetic subjects. *IEEE Trans Neural Syst Rehabil Eng* 21:198–207. <https://doi.org/10.1109/TNSRE.2013.2238250>

Wang W-E, Ho RLM, Gatto B, van der Veen SM, Underation MK, Thomas JS, Antony AB, Coombes SA (2020) A novel method to understand neural oscillations during full-body reaching: a combined EEG and 3D virtual reality study. *IEEE Trans Neural Syst Rehabil Eng.* <https://doi.org/10.1109/TNSRE.2020.3039829>

WMA (World Medical Association) (2009) Declaration of Helsinki. Ethical principles for medical research involving human subjects. *J Indian Med Assoc* 107:403–405

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