Study of full-body virtual embodiment using non-invasive brain stimulation and imaging

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Abstract
The sense of embodiment in virtual reality is a strong case of body ownership illusion, effectively allowing humans to experience the ownership of a modified, or a completely different body. Virtual embodiment has captured the attention of researchers in various fields, with applications far beyond computer science. Despite the promising applications, little is known about the neural mechanisms behind full-body virtual embodiment. This study investigates the influence of anodal transcranial direct current stimulation of the brain area linked to processing of the bodily self (right temporoparietal junction) to the subjective strength of virtual embodiment and its main constituents, using within-subject experimental design with sham-controlled stimulation. Virtual embodiment was studied using questionnaires, accompanied by brain signals gathered using EEG. Our results suggest that stimulation did not affect the sense of ownership towards the virtual avatar. Borderline strengthening of the perceived sense of agency towards the avatar's actions was found in the sessions with stimulation.

KEYWORDS
virtual embodiment; virtual reality; transcranial direct-current stimulation; electroencephalography; sense of ownership; sense of agency

1. Introduction

Virtual reality (VR) is becoming increasingly popular thanks to the advances in technology and lowering costs of the consumer equipment. Popularity of VR in research beyond the computer science field is not surprising – VR is the technology that allows for fabrication of scenarios unlikely or impossible to be reconstructed in the reality. Usually, this means transporting users to distant or made-up worlds (Whyte, 2002), but immense potential lies also in the possibility to manipulate representation of the user's body – the virtual avatar.

Embodiment in VR is a vital part of the VR experience, denoting the ability to "own" and operate a surrogate body in VR, in the same way as if it was the own body (Kilteni et al., 2012). Embodiment into the virtual avatar occurs despite imperfect sensory stimulation lacking for example the tactile feedback. Synchrony between the

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performed motor actions and the visual stimuli rendered in VR has been demonstrated to be sufficient to create a strong body ownership transfer illusion, allowing the avatar embodiment (Sanchez-Vives et al., 2010; Slater et al., 2010).

Virtual embodiment is also an interesting research tool for neuroscientists and psychologists. Similarly to the body ownership illusions created without VR (Botvinick and Cohen, 1998; Kalckert and Ehrsson, 2014), full-body virtual embodiment helps researchers to understand the brain mechanisms behind body self-recognition and action self-attribution. Experiments with the virtual body representations revealed that users can control bodies different from their own (in terms of shape and size) (Nishida et al., 2019; Tajadura-Jiménez et al., 2017), diverging from the humanoid structure (Javorský et al., 2018) with extranumerous limbs or added non-human body parts (Steptoe et al., 2013; Won et al., 2015), or animal bodies with no resemblance to the humanoid body (Krekhov et al., 2019; Oyanagi and Ohmura, 2019).

An interesting effect complementing the embodied VR experience is the Proteus effect (Yee and Bailenson, 2007), describing high-level changes to one's behavior in virtual and on-line environments according to the characteristics of the virtual body one has been embodied into. This effect can even outlive the VR experience, making Proteus effect interesting for the research in psychology. Due to the enhanced perspective taking, participants can break their habitual form of thinking about their personal problems, consequently leading to improvements in mood (Osimo et al., 2015), self-compassion in depressive patients (Falconer et al., 2016), and emotion recognition abilities in domestic violence offenders after virtually swapping roles with the victims (Seinfeld et al., 2018).

Despite its promising applications, virtual embodiment is far from being fully understood. There are hypotheses on its emergence, based on interplay between bottom-up multisensory processing (integrating data from multiple sensory channels) and top-down predictions (Gonzalez-Franco and Lanier, 2017), but explanation on the neural level is largely missing. Identification of neural correlates of the virtual embodiment would allow objective evaluation using neuroimaging methods. This study aims to contribute to the understanding of low-level mechanisms behind the virtual embodiment, and their link to the subjective manifestation. Past research has demonstrated importance of a small part of the brain, the right temporoparietal junction (rTPJ), during manifestation of the body ownership illusions (Convento et al., 2018). Specifically, rTPJ seems to play a role in the multisensory integration process that facilitates building of the bodily self from the available sensory data (Blanke et al., 2005).

This paper presents an investigation into influence of the rTPJ processing on the full-body virtual embodiment in VR. Firstly, non-invasive brain stimulation was directed to the rTPJ (transcranial direct current stimulation, tDCS, was utilized). Secondly, subjective reports on virtual embodiment were collected using questionnaires and activity over both temporoparietal junction areas and the sensorimotor cortex was measured using electroencephalography (EEG). Our hypothesis was that the increased cortical excitability caused by the anodal tDCS would lead to strengthened subjective sense of embodiment in VR, while the EEG data served as complementary measure underpinning questionnaire responses. Furthermore, motion tracking data on user behavior in the VR scene (obstacle avoidance during the tasks) were utilized to complement the questionnaires.

To investigate our hypothesis, sham-controlled within-subject study was conducted. Total of 10 participants volunteered in two sessions, where they received anodal or sham tDCS for 15 minutes (sham tDCS means that the stimulation protocol was followed, but without an effective dosage of the stimulation). Participants then experienced a short VR exposure consisting of several tasks focused on virtual body self-observation, locomotion, hand-object manipulation, and illusory (visually-induced) touch sensing.

2. Background

2.1. Structure of the cortex and the EEG

To collect real-time physiological data from the brain, several imaging techniques are commonly employed by the researchers. Functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) are among the widely used brain imaging techniques, but they depend on large equipment which effectively immobilizes the participant. A popular neuroimaging method is the EEG. EEG records electrophysiological signals, the neural oscillations, corresponding to summation of electrical discharges from large patches of neuronal cells with similar spatial orientation (Cohen, 2017). Typically, the EEG signal is recorded simultaneously from multiple electrodes placed on the scalp (EEG channels) against a non-encephalic reference electrode. Location of the EEG sensors is typically determined by the 10-20 international system for electrode positioning (Homan et al., 1987). Temporal resolution of the EEG is in order of milliseconds, allowing to record changes in neural oscillations following time-locked events with great precision (Gevins et al., 1995). Downsides of the EEG result from the necessity of the signal to pass through various tissues, especially the skull. Resulting main drawbacks of EEG are a poor spatial resolution and high susceptibility to noise. Besides the environmental noise, bodily movements are contaminants of the signal, as electrical signaling in muscles tends to overpower the brain sources of the signal. Participants are typically disallowed to move during an EEG investigation, or only a limited movement is permitted.

Human brain is a bilateral, mostly symmetrical structure with functionally distinct areas. Scalp EEG cannot be used to record arbitrary brain signals, but is limited mainly to recording of the signals from the youngest part of the brain, the cerebral cortex. This part of the brain is responsible for higher functions, such as those requiring cognitive activity (Kandel et al., 2000). Cortex forms the outer part of the human brain and is further divided into functionally specialized lobes; the frontal, parietal, occipital, and temporal lobes. Of interest for purposes of this study was mainly the sensorimotor cortex composed of somatosensory cortex (located in the parietal lobe; its function include perception of somatic inputs and multisensory integration) and the motor cortex (neighboring with the somatosensory cortex, but located in the frontal lobe; its main function concerns planning, programming, and executing motor actions). Small cortical area called the temporoparietal junction (TPJ) is of special interest as a large portion of multisensory integration and building of the unified self-image originates there (Arzy et al., 2006).

One of the most common methods in EEG signal analysis focuses on the band power of neural oscillations in the previously identified frequency bands: delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30 Hz or more) (Niedermeyer and Lopes da Silva, 2005). Neural oscillations of the same frequency can be of various origins within the brain, and each of these bands has associated functional correlates (with respect to the brain area of origin). Alpha oscillations were analyzed in scope of this study, as they accompany cortical inactivity Laufs et al. (2003), and decrease in the alpha amplitude correlates with increased processing in the underlying cortical areas.

2.2. Non-invasive brain stimulation

Non-invasive stimulation using direct current (the tDCS) belongs to the family of transcranial electric stimulation, together with transcranial alternate current stimulation (tACS) (Reed and Cohen Kadosh, 2018). While stimulation with tACS leads to neuronal entrainment and causes immediate changes to the neuronal communication (Antal and Paulus, 2013), application of the tDCS leads to subthreshold changes in resting cell membrane potential, in turn causing excitability changes to the cortical neurons (Reed and Cohen Kadosh, 2018). In practice, the neurons are more or less likely to communicate after a tDCS intervention.

A weak direct electrical current (1-2 mA are common) is applied during tDCS (Woods et al., 2016). The procedure requires at least one anode and one cathode electrodes to be placed on the scalp. Although more than two electrodes can be used, the minimal set-up involves one active electrode for the stimulation (anodal stimulation uses anode as the active electrode, while cathodal stimulation utilizes active cathode) and one return electrode (Woods et al., 2016). The one-way current flow in the tissue typically causes increases in the excitability of neurons close to the anode and decreases in excitability under the cathode (Reed and Cohen Kadosh, 2018). Besides intensity of the current, length of the stimulation modulates duration of the effects, which typically outlive the intervention for minutes to hours depending on the parameters (Nitsche and Paulus, 2001). tDCS is a widely used research tool with a low number and severity of the adverse effects, mostly concerning of occasional physical discomfort (Matsumoto and Ugawa, 2017).

2.3. Body ownership, embodiment, and VR

One of the fundamental aspects of the VR (although still not widely exploited in the current commercial applications due to lack of full-body VR systems) is its ability to accurately overlay the visual representation of the user's body. This possibility to receive a new body is a complement to the traditionally discussed purpose of the VR; to transport people into foreign or made-up places. Even in absence of the tactile or vestibular stimulation, users in VR act as if they were in the place depicted by the VR scene (*place illusion*) and as if the events were actually occurring (*plausibility*), both despite knowing they are in a synthetic virtual world mediated by technology (Slater, 2009). Similarly, the render of a new body is accepted with ease by the users, even in cases when the virtual body substantially differs from the human body (this malleability has been termed *homuncular flexibility*; Krekhov et al. (2019); Won et al. (2015)).

VR embodiment has been studied extensively in the last decade. Most authors agree on three components underlying the sense of embodiment put forward by Kilteni et al. (2012): the *sense of ownership* (SoO) and the *sense of agency* (SoA) towards the foreign body, and the *sense of self-location* in the new body. The SoO denotes self-attribution of the body (i.e., having the virtual body in the possessive meaning), and the term SoA is used to denote the experience of being the author (agent) of voluntary actions performed with the avatar (Gallagher, 2000). Sense of self-location depicts the egocentric frame of reference in processing of the sensory data (first-person perspective).

The sense of embodiment is believed to emerge from manipulation of the top-down predictive mechanism of self-recognition by the illusory stimulation, i.e. visual feedback that is different than seeing own body, but still considered plausible due to its congruency to the executed motor actions (Gonzalez-Franco and Lanier, 2017; Sanchez-Vives et al., 2010). When the bottom-up multisensory integration of congruent stimuli does not significantly interfere with the expected top-down predictions, a person is embodied in his/her virtual representation. VR eventually proved to be a useful tool for investigation of the body ownership illusions in the full-body setting (Maselli and Slater, 2013). Usage of HMDs allows for superhuman experimental scenarios such as body swapping (Petkova and Ehrsson, 2008), out of body experiences (De Oliveira et al., 2016; Lenggenhager et al., 2007), or teleoperation of humanoid robots using body tracking (Nishio et al., 2018) or even brain-computer interfaces (Alimardani et al., 2016).

Transfer of body ownership facilitated by the congruency between motor actions and visual stimulation is similar to the body ownership transfer created by synchronous stimulation of other senses. First scientific description of this phenomenon was offered by Botvinick and Cohen (1998) in their famous rubber hand illusion (RHI). During the RHI, a participant receives tactile stimulation on her hand, but the hand is hidden from her sight. Instead, a rubber hand is placed in the visual field oriented congruently to the real hand. Experimenter then proceeds to touch the rubber hand with a paintbrush in synchrony with the real hand. The illusory effect is that participant gradually starts to feel that the rubber hand is her own, and that the touch is felt at the location of the rubber, instead of her real hand. In the following years, numerous variants of the RHI were developed, as well as adaptations of the original illusion in VR and augmented reality (Raz et al., 2008; Škola and Liarokapis, 2016), and even a virtual hand illusion variant showing feasibility of embodiment induced via brain-computer interace control (Perez-Marcos et al., 2009; Škola et al., 2019).

The central part in the virtual embodiment is the representation of the user's body – avatar. Similarly to the RHI which arises with a rubber representation of the hand, also the virtual embodiment "works" with non-photorealistic visual representations of the body (such as wooden dolls or cartoon-like characters) (Lugrin et al., 2015) or avatars visually different from the user's body. Deliberate changes to the avatar have been further leveraged as perspective taking tools in the Proteus effect (Yee and Bailenson, 2007). Due to Proteus effect, usage of a generic avatar might be preferred in research for minimization of possible avatar appearance effects on the participant behavior. Proteus effect manifests in changes to one's self-image, behavior (Kilteni et al., 2013), and attitude (Banakou et al., 2013; Peck et al., 2013) according to the characteristics of the avatar appearance (e.g., skin color in Peck et al. (2013), figure in Normand et al. (2011), and age and size in (Banakou et al., 2013; Tajadura-Jiménez et al., 2017)). It has also been demonstrated that adding possibility to interact socially influences participants in a VR setting (Roth et al., 2018), which can be exploited in combination with real-time EEG measurements in a brain-computer interface (Roth et al., 2019a,1).

Measuring of the magnitude of the virtual embodiment and its components (mainly the SoO) is a non-trivial problem. Strength of the illusory effect in the RHI was assessed using questionnaires and a measure termed proprioceptive drift (the difference between the perceived and the actual hand position), but in VR, this proprioceptive conflict is missing (if it is not induced artificially). Embodiment in VR is commonly assessed by questionnaires (see, e.g. Gonzalez-Franco and Peck (2018); Roth et al. (2017)) and sometimes using measurements of the induced stress after a threat to the virtual body

(Armel and Ramachandran V. S., 2003).

In this paper, the term “virtual embodiment” is used to denote the sense of embodiment towards the virtual avatar, denoting the experience of being collocated with the avatar, being in control (the SoA), and having the SoO for the avatar. This is the definition put forward by Kilteni et al. (2012). Another notable definition of virtual embodiment was proposed by Spanlang et al. (2014), who describes it as the physical process of substitution of one’s body using the VR hardware and software. From their perspective, the SoO and the SoA are products of virtual embodiment, not its prerequisites.

2.4. Role of TPJ in body ownership and multisensory illusions

Blanke et al. (2005) investigated roles of the TPJ in mental transformation of the frame of self-reference to an out-of-body perspective. Firstly, EEG mapping of evoked potentials showed there was a selective TPJ activation shortly after the onset of the imagined self-perspective transformation. Secondly, transcranial magnetic stimulation (TMS) was utilized to disrupt the TPJ function in the interval of the TPJ activation, which resulted in an impaired performance in the mental self-perspective transformation task. Based on these results, authors argued for an importance of the TPJ in the maintenance of a coherent self-image, including the spatial unity of the self and the body.

Study by Tsakiris et al. (2008) utilized TMS to disrupt the rTPJ function which resulted in disruption of the participants’ bodily self-attribution ability, creating additional evidence that the rTPJ is involved in maintaining spatial unity by integrating inputs from the variety of sensory channels. Another study using a single-pulse TMS delivered to the rTPJ during multisensory conflicts found out an increased ability to resolve the visuo-tactile conflicts during a mirror-box illusion (Papeo et al., 2010). Authors suggested that the rTPJ plays a role in the detection of multisensory conflicts, rather than their correction. Convento et al. (2018) performed tDCS intervention in the RHI, using anodal stimulation focused to either the rTPJ, or the right premotor cortex. Stimulation led to misattribution of the own hand position in favor of the rubber hand position (in case of both rTPJ and premotor cortex stimulation), while the rTPJ stimulation also increased difference between the synchronous and the asynchronous (usually the control) condition for the RHI. Subjectively, participants reported stronger perception of the illusory touch on the rubber hand (question “It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.”).

Activation of the TPJ frequently accompanies actions where self-other distinction must be processed (Decety and Sommerville, 2003), which consequently links it to the SoA (which is judged based on a comparison between the performed action and the observed outcomes; Decety and Lamm (2007)). Evidence is provided by SoA studies showing the rTPJ activation (Farrer et al., 2003; Farrer and Frith, 2002); specifically in Farrer et al. (2003), the rTPJ activation was inversely proportional to the perceived level of control of a virtual hand.

Studies using brain stimulation allowed to establish a causal link between the TPJ and the SoA. Repeated TMS of rTPJ enhanced (Heinisch et al., 2011,1; Uddin et al., 2006) and anodal tDCS decreased (Payne and Tsakiris, 2017) self-recognition (self-other face discrimination) ability in face-morphing tasks. Cathodal tDCS did not reverse the effect (self-recognition was not enhanced following the cathodal tDCS). This may be due to the fact that although cathodal tDCS often leads to inhibition when aiming at motor functions, possible inhibitory effects of the cathodal stimulation aiming at the cognitive functions is likely compensated by rich neural networks concerned with cognitive processing (Jacobson et al., 2012).

In this study, we hypothesized that the anodal tDCS over rTPJ would extend the sense of embodiment by increasing neural firing in the area, with the primary effect on the self-recognition. Possible mechanisms range from the increased SoO for the avatar caused by disrupted self-recognition mechanism (by increased rTPJ activity), to the increased SoA, allowing for easier acceptance of the foreign body by means of lower threshold in action self-attribution. As the effects of tDCS can be both stimulation or inhibition of neural communication, observing any effect would greatly help in clarification of the rTPJ stimulation effects on the sense embodiment.

3. Materials and Methods

3.1. Participants

This study utilized a within-subject design, with 10 participants (6 male and 4 female; mean age = 28.769, SD = 3.609) attending two sessions. The study had a single-blind design, where in one session the participants were stimulated and in the the other session, sham stimulation took place. Sham stimulation protocol was designed so the participants could not be sure which session employed the active stimulation and which not. Stimulation and sham conditions were counter-balanced, and both of the sessions took place within one week (but not on two consecutive days).

Participants were provided with an informed consent containing introductory information about VR, tDCS, and EEG. Nevertheless, the purpose of the study (measuring and comparing virtual embodiment) was not revealed before the experiment, and participants received the information that purpose of the study is to measure the effect of stimulation to VR experience overall. The study was approved by the ethics committee of Masaryk University.

3.2. Tools and Measures

3.2.1. Stimulation

For the purpose of rTPJ stimulation, the active electrode was placed at the CP6 position (according to 10-20 international system for EEG recording) and the return electrode was placed on the vertex (Cz position in the 10-20 system). In span of the two experimental sessions, participants received anodal stimulation and sham stimulation. Stimulation was performed with two saline-soaked (0.9% NaCl solution) circular sponge electrodes with surface area of 25 cm2. Stimulation current was 1.25 mA, with duration of 15 minutes (including 5 seconds of ramp-up and 5 second of ramp-down). The selected duration should affect the underlying area for more than an hour after the stimulation (Nitsche and Paulus, 2001).

Sham-stimulation procedure was identical to the active stimulation; i.e., the electrode cap with two saline-soaked electrodes was prepared and positioned on the participant and impedance check was performed. After the impedance was satisfactory, a process resembling the real stimulation was initiated. However, only the initial and final 5 seconds of stimulation were delivered (instead of 15 minutes). Neuroelectrics

Starstim 8 (Neuroelectrics, Spain) was utilized for the stimulation procedure.

3.2.2. EEG

EEG recording was performed with 7 AgCl gel-based sensors (NG Geltrode) placed over the sensorimotor cortex (positions CP3, CP1, CPz, CP2, CP4), the rTPJ (CP6), and the left TPJ (CP5). Common mode sense/driven right leg (CMS/DRL) earclip was placed to the right ear as the signal reference. Due to the subject limitations during EEG recording (bodily movements should be avoided), only data from the movement-free parts of the experiment were evaluated. For this purpose, participants were asked to stay relaxed and still for 7.5 seconds on three occasions during the experiment. Starstim 8 was used for the EEG recording procedure as well.

3.2.3. Questionnaires

Pre-experimental questionnaire surveyed the demographics and participant's experience with the VR and frequency of playing computer games. After the end of the VR session, participants received another questionnaire surveying virtual embodiment, affect, judgment of the VR environment, and experience consequence (VR sickness). Affect, judgment, and the experience consequence were surveyed to rule out negative influence of the stimulation onto the VR experience. The last question of the questionnaire was dedicated to participant's opinion regarding the mode of stimulation (sham/real) and confidence of the guess. All the quantitative parts of the questionnaire were answered on a 7-point Likert scale, ranging from -3 "Not at all", through 0 "Somewhat", to +3 "Completely".

Virtual embodiment was surveyed using questions adapted from the article by Gonzalez-Franco and Peck (2018). In their attempt to create a standardized embodiment questionnaire, they assessed the avatar embodiment on the following subscales: body ownership (SoO), agency and motor control (SoA), tactile sensations, location of the body, response to external stimuli, and the external appearance. The questions in judgment and experience consequence scales were adopted from Tcha-Tokey et al. (2016).

Subscales for the SoO, the SoA, tactile sensations, external stimuli, and location from the avatar embodiment questionnaire were utilized in the experiment. The tactile sensations subscale was utilized, but it was used for assessment of the illusory touch perception (subjective tactile sensations emerging after observing visually presented tactile stimulation with absence of real touch, see Škola and Liarokapis (2019)). For this reason, only questions regarding subjective tactile perception were kept from the category (Q10, Q13 in the paper by Gonzalez-Franco and Peck (2018)) and questions regarding localization and origin of the tactile stimuli were removed. Two questions ("I felt as if the falling virtual balls touched my arms or hands" and "I felt as if my feet or legs touched the virtual balls") were added to aid investigation of the illusory touch. Subscale surveying the participant response to external stimuli was reduced as well (Q22 and Q24 were not used). This subscale has been designed to survey participant's reaction to a threatening stimulus during virtual embodiment. We decided to employ only non-threatening stimuli during the experiment (i.e., task 4), due to the usage of a within-subject design.

Figure 1. (Top left) Detail of EEG and HMD positioning, (Top right) Position of hand and waist tracking belt, (Bottom left) Position of waist tracking point, (Bottom right) Position of feet trackers

3.2.4. VR equipment

The study utilized an immersive VR system based on state-of-the-art HTC Vive Pro HMD. Participants held Vive controllers in their hands for the duration of the experiment. To track position and orientation of feet for purposes of full-body avatar reconstruction, Vive trackers were mounted on the legs (above the ankles, as displayed on Figure 1). One tracker with the purpose to track the orientation of the body was placed to the back (see also Fig. 1).

3.2.5. VR scene

VR environment for the experiment was set in a small house and its vicinity (see Figure 2). There were two rooms in the house, separated by a wall. First room was where the experiment started; it contained enough free space and a mirror, as embodiment into the avatar took place in this room. Second room contained a table with five

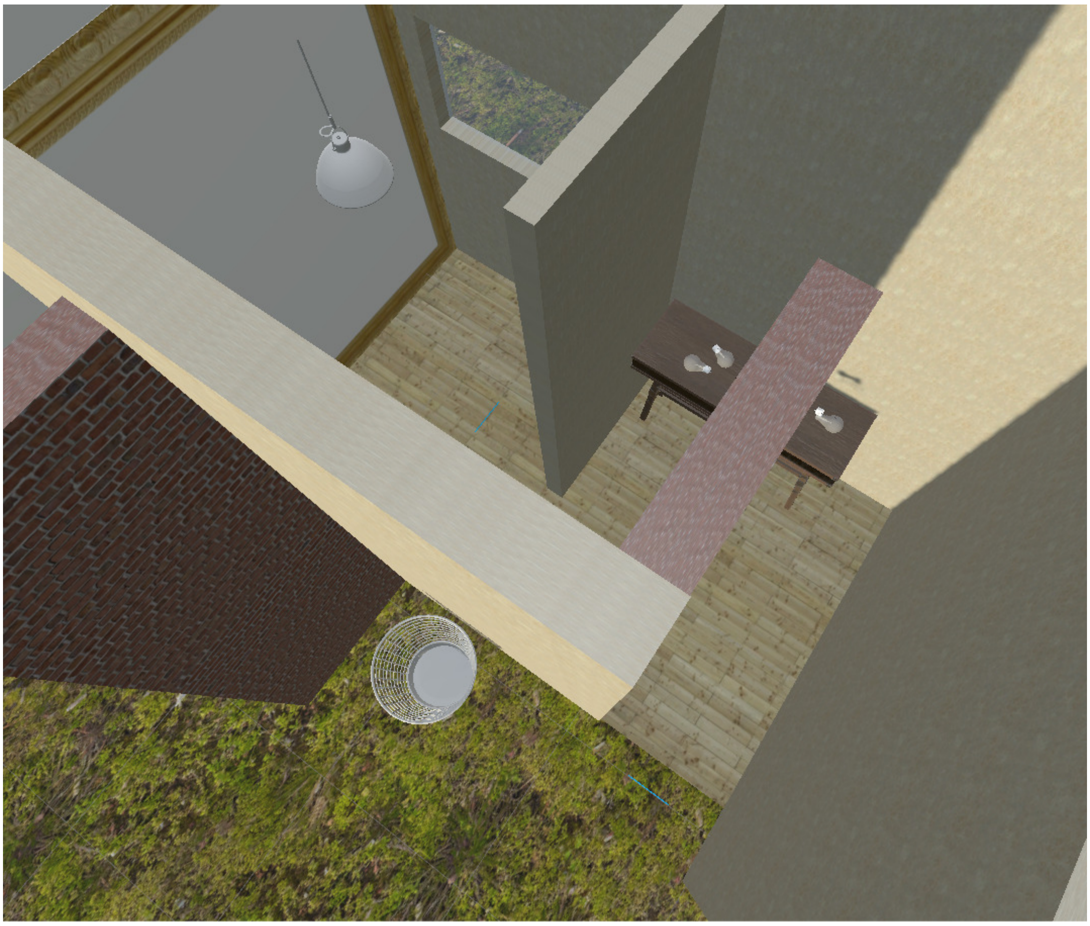

Figure 2. Overview of the virtual scene. Participant started the series of tasks in the top-left room of the house, where the mirror was located (shown without the reflection on this Figure).

Figure 3. Screenshots from the experimental tasks in VR (cropped; participants had a larger field of view in the HMD compared to the PC display). Picture on the left is taken from task 3, the figure in the middle depicts part of task 1, and a screenshot from task 2 is presented on the right.

lightbulbs. Part of the second room was a passage leading to the outside of the house, the transition between indoors and outdoors was marked with a short blue line. The distant surrounding of the virtual house was composed of aerial view on a landscape, and the house appeared to be located on a heightened platform. It was not possible to reach the end of the area due to the room size and cabling of the HMD. The scene was developed using Unity (Unity Technologies, USA), and the details of the scene as well as the experimental tasks can be seen in the video accompanying this paper[1].

3.3. Tasks

Participants performed a set of simple tasks in the VR environment, with the purpose to become acquainted with the representation of their virtual body. The tasks were adapted from the previous research on avatar embodiment (Koilias et al., 2019; Waltemate et al., 2018), and focused on self-observation of the virtual body, hand-object manipulation, foot-object interaction, locomotion, and the illusory touch.

EEG signals were recorded immediately after the first stage of the virtual embodiment (after task 1). Secondly, the EEG signals after finishing the rest of the tasks were recorded (with presumed stronger sense of embodiment after following the whole procedure). Task 2 served to strengthen the sense of embodiment, tasks 3 and 4 served to investigate into the illusory touch. Application screenshots from various parts of the tasks are displayed in Figure 3.

3.3.1. Task 1: self-observation

Participants were instructed to turn to the left where a mirror was located, and to step onto a defined position on the floor (marked by a short blue line). Experimenter then started to instruct through the procedure of the avatar body observation. The exact instructions were as follows:

(1) *Extend your left arm in front of you and look at your hand. Now use the trigger to form a hand grip and observe the hand in grip.*
(2) (The above step was repeated with the right arm/hand)
(3) *Look down to your feet and raise your left knee a little bit.*
(4) (The above step was repeated with the right leg/knee)
(5) *Now, look at the mirror and extend your arms to the sides.*
(6) *Put your hands back. Wave to yourself in the mirror.*

EEG signals corresponding to the *phase I embodiment* were recorded after task 1, while the participant stood still and watched the mirror reflection of the avatar. After finishing the task, experimenter instructed the participant to turn around and find and enter the second room.

3.3.2. Task 2: hand-object manipulation

In this task, participants picked up small virtual objects (lightbulbs) from a virtual table and transferred them into a virtual trash bin located several meters from the table, behind a corner, outside the house. Five lightbulbs were to be transferred by the participants. This task familiarized participants with avatar hands using simple manipulation, and required body coordination with obstacle avoidance. In effect, participants

[1] `https://www.youtube.com/watch?v=zFv7CRIxSrc`

became aware of the properties of their virtual bodies in action (during locomotion), while trying to avoid colliding with the obstacles (virtual walls and objects) in the VR environment.

3.3.3. Task 3: foot-object interaction

Participants were asked to stand on a blue mark at the entrance to the house (facing outdoors), while a virtual ball (20 cm in diameter) descended on the floor ahead of them. The goal of this task was to move the ball using a gentle leg motion. In total, 10 balls were to be kicked; after each ball exited the virtual space, another ball approached the participant. Although the instruction was to kick the ball from the platform, it was not necessary to achieve its repositioning to any specific place, only to set it to motion. In case the ball did not fall from the platform, experimenter removed it from the area. Apart from engagement of the legs, sense of illusory touch (actively generated) was also assessed based on this task.

3.3.4. Task 4: illusory touch sensing

This task required the participants to stand still with their hands extended in front of them. A sequence of small balls with 15 cm diameter materialized 1 m above the extended arms sequentially and fell to arms and hands in span of 16 secs. For the participant, this task consisted of passive observation of the ball-arm interaction, while its purpose was assessment of a passively sensed illusory touch.

3.3.5. Task 5: return

Participants were asked to return to their initial position inside the house, in front of the mirror. Purpose of this task was to assess collision avoidance after advanced embodiment into the avatar during a low variance in the route. However, after analyzing the collision data from the task 5, it was decided to analyze collisions generated during the entire experiment instead, as majority of the participants generated no collisions during this task.

Upon returning, participants were instructed to step on the blue mark to the same position as in the beginning of the experiment (while looking into the mirror), and EEG data corresponding to *phase II embodiment* were recorded.

3.4. Procedure

The procedure of the experiment is shown in Figure 5. Firstly, participants went through the briefing and pre-experimental questionnaires. As the next step, they were seated and their head dimensions were measured (nasion-inion and ear-to-ear distances). Cap with the stimulation electrodes was set-up (approx. 10 minutes) and either sham or active stimulation followed for 15 mins.

EEG electrode set-up (gel application, impedance check) took place immediately after the end of the stimulation procedure (approx. 10 mins), followed by the set-up of VR equipment (5 mins). In the last step, participants received HMD (mounted with the help of the experimenter). Now fully immersed into the VR space, participants were instructed to position themselves to the starting position and to personalize the inter-ocular distance of the HMD in case it was necessary, then the VR controllers were handed over. Immediately before launching the experimental application, participants

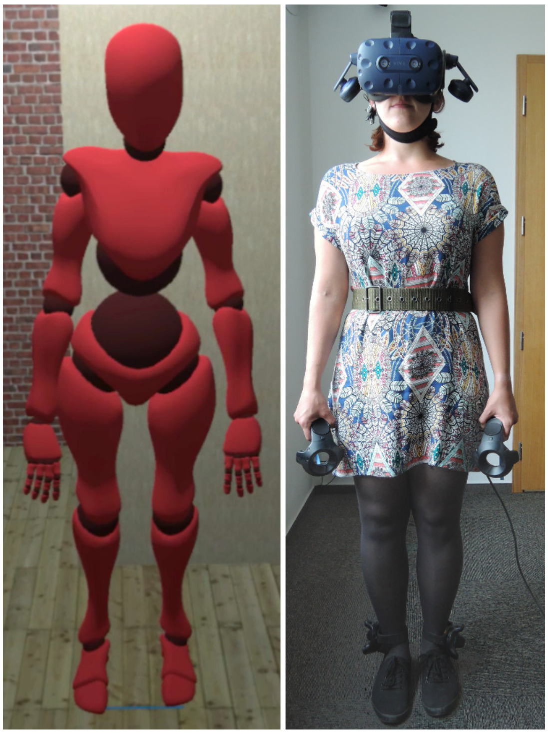

Figure 4. Virtual avatar and participant wearing all equipment.

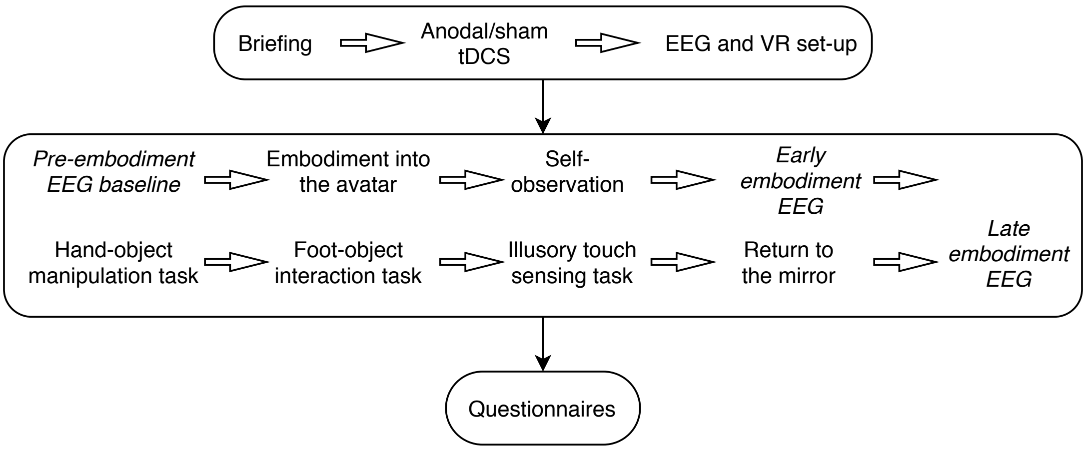

Figure 5. Diagram showing the procedure of the experiment. Text in italics indicates the EEG recording phases, while all the activities between the first and the last EEG measurement were performed in VR.

were instructed to close their eyes (for the period of the start-up of the application).

After opening their eyes, participants found themselves in the virtual environment of the experimental application, standing behind the avatar. In the first phase, participant did not have the avatar body assigned, and only the controllers and trackers were visible in the scene (to keep consistency with the VR set-up scene preceding the experimental one). Participant was transferred into the avatar body after recording the initial segment of EEG data (pre-embodiment baseline). At this point, the participant was positioned in a small room inside a house, oriented towards a wall with a window.

As the next step, participants were embodied in an androgynous non-photorealistic virtual avatar obtained from Mixamo[2]. Control of the avatar was mediated using six points tracked in the physical space, representing the head (tracked with the HMD), hands (tracked using the controllers), waist (tracked using the tracker, positioned on a belt), and feet (tracked using trackers positioned on ankles). Figure 4 shows the avatar and participant wearing all the equipment required for the experiment. Position and rotation of the rest of avatar's body parts was computed using inverse kinematics mechanism built in Unity.

Participants were informed that no obstacles are present in the physical space that would collide with the virtual space, with the exception of the outer walls of the building indicating the walkable area. Artificial obstacles in form of the inner walls were created to raise participants' awareness of the avatar body during locomotion. This was adapted from the discussion of a study on avatar embodiment (Koilias et al., 2019), where participants during locomotion in a space without obstacles reported low awareness of the virtual body.

VR phase took approx. 7-10 minutes. The experiment consisted of a series of tasks guided by the experimenter, who watched progress of the participant on the screen. Experimenter helped the participants to take off the equipment after the end of the VR phase and handed over the questionnaires. The session was ended after the questionnaires were returned.

3.5. Data analysis

3.5.1. EEG signal processing

Cleaning of the EEG data consisted of downsampling to 100 Hz (resulting in clearance of the 50 Hz line noise) and high-pass filtering at 1.5 Hz. Due to the low number of electrodes employed for recording, no interpolation or signal reconstruction methods were used in the post-processing phase. We also did not encounter issues in the signal quality, as the electrodes used for recording did not interfere with the scaffold of the HMD. It has been demonstrated that EEG signals are largely unaffected by the usage of HMDs (Hertweck et al., 2019). To assure that the signal used in the analysis was not contaminated with movement, motion tracking data from the HMD and both controllers were utilized to ensure no movement occurred during the instructions to stay still. Moreover, visual inspection of the signals was performed before the analysis.

Total of 3 epochs (7.5-second long) were generated from each recording: pre-embodiment baseline, *phase I embodiment*, and *phase II embodiment*. The EEG channels were split into three areas of interest: CP6 (over the rTPJ), CP5 (over the left TPJ), and the sensorimotor channel set (composed of averaged spectra from channels

[2] `https://mixamo.com`

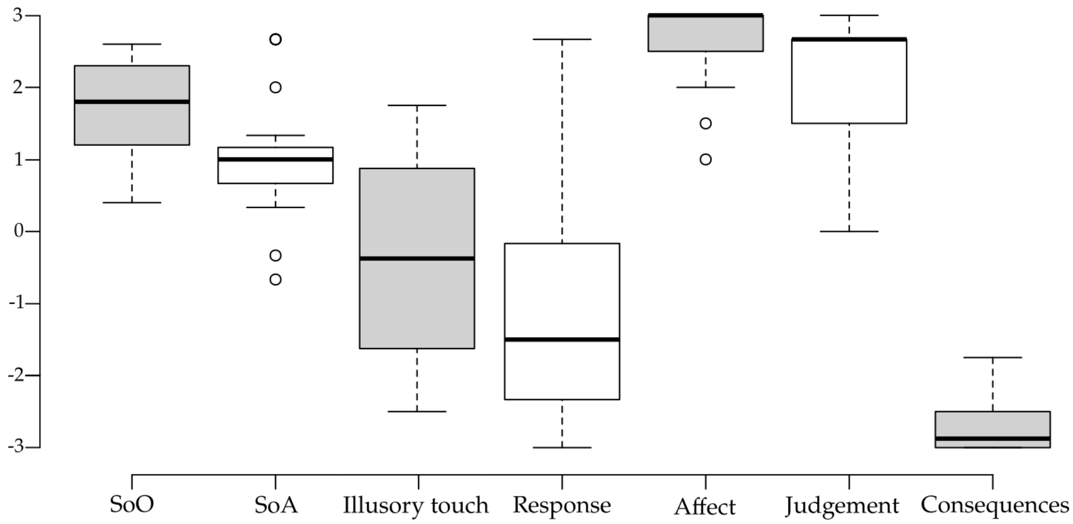

Figure 6. Boxplot with all the questionnaire subscales, aggregated from both sessions.

CP3, CP4, CPz, CP1, and CP2). The values of interest were changes in channel spectra; between the pre-embodiment baseline and each of the two phases of embodiment. The spectral values were gathered using mean power spectral density computation (*spectopo* function in EEGLAB). The percentage change in EEG spectra is reported for the whole 7.5-second epoch.

3.5.2. Statistical testing

Non-parametric statistical tests were used to evaluate the data. Spearman test was used to find correlations in the data, and within-group differences were computed using Wilcoxon rank sum test. Statistical testing was carried out in R and IBM SPSS. Correlations were evaluated regardless the condition (stimulated/sham-stimulated), resulting in number of cases N = 20.

4. Results

4.1. Subscale consistency

All quantitative questions in the questionnaires were responded on a 7-point Likert scale (min = -3, max = +3), while questionnaire subscales consisting of several individual questions were normalized (divided by the number of questions per category). Cronbach Alpha was used to determine internal consistency of the subscales. Two subscales resulted with a negative alpha coefficient; SoA and Location. SoA was corrected by removal of the question Q9 *I felt as if the virtual body was moving by itself* which was then evaluated separately (resulting SoA alpha coefficient = 0.329, which was still not very high). Subscale Location, composing of just two questions, was excluded from the analysis (see Section 5 for further details).

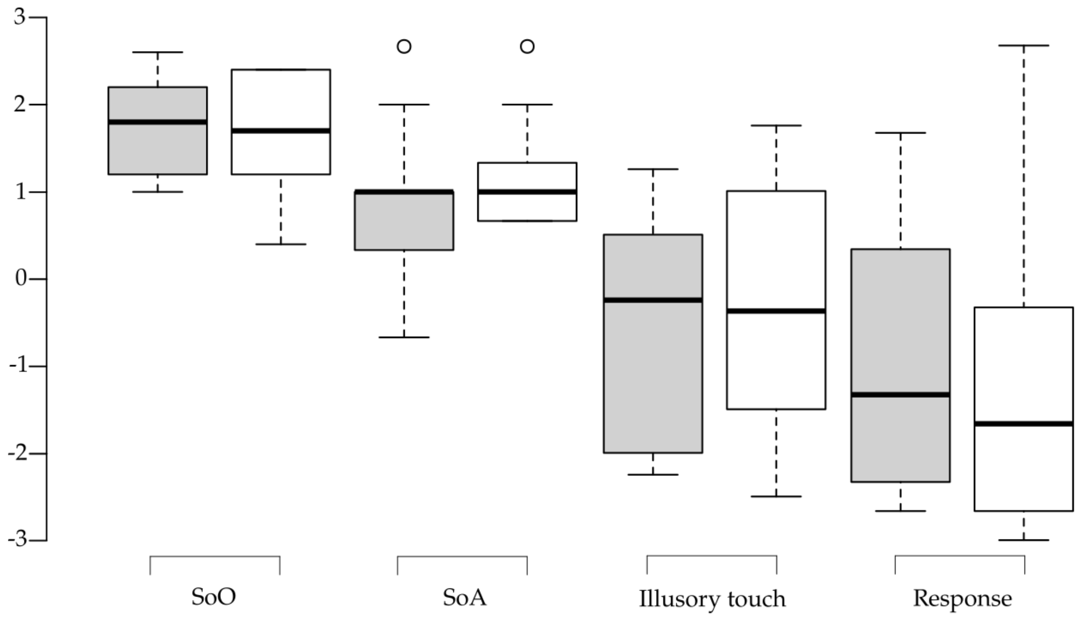

Figure 7. Boxplot with differences between the non-stimulated (on the left and in gray) and the stimulated (on the right and in white) condition per each category of the avatar embodiment questionnaire.

4.2. Embodiment

Descriptive statistics for the sense of embodiment subscales (both sessions) are presented in Figure 6, together with the descriptives for the rest of the questionnaire. All the main subscales of virtual embodiment (SoO, SoA) were also in the positive part of the scales; mean SoO = 1.7, SD = 0.617; mean SoA = 1.03, SD = 0.898. It should also be noted that the SoO and the SoA did not always go hand in hand (r = 0.290, p = 0.215).

4.3. Effect of stimulation

Statistical testing of the questionnaire differences between groups was performed to reveal the effects of stimulation to the perception of the VR experience. The expected difference in the SoO scale was not found (V = 29.5, p = 0.440), nor were found statistically significant differences in the alpha band activity over rTPJ or other areas.

Results showed a statistically non-significant (V = 2, p = 0.052) strengthening of the SoA following the stimulation (mean = 1.167, SD = 0.671) compared to the sessions with sham-stimulation (mean = 0.833, SD = 0.997). Descriptive statistics showing the differences between stimulated and non-stimulated sessions are shown in Figure 7.

4.4. Correlations

4.4.1. EEG correlates of the SoO

Correlations between the EEG results and the subjective responses were investigated to find candidates for the neural correlates of the SoO. Theta band power change over the sensorimotor cortex channel set (r = -0.635, p = 0.003) and theta band power change at CP5 (r = -0.611, p = 0.005), between the pre-embodiment baseline and the *phase I embodiment* (in both cases) were correlated to the SoO subscale (the increased SoO was associated to the decreased theta oscillations).

4.4.2. Behavioral correlates

Mean duration of avatar-wall collisions in the session was 1.476 seconds (SD = 2.407). There was a trend of the SoA to negatively correlate to the total duration of collisions (r = -0.412, p = 0.071).

4.5. Other results

4.5.1. Illusory touch

Illusory touch was not influenced by tDCS, but the illusion was present in the experiment (mean = -0.4, SD = 1.387). Rating of illusory touch was not stronger in the second session (V = 21, p = 0.541) as was the case in our previous study (Škola and Liarokapis, 2019), probably due to a richer environment that was not focused solely on the illusory touch sensing (as was the case of the last study).

4.5.2. Behavior in VR environment

All participants complied with the real-world-like limitations of the virtual environment; i.e., they tried to actively avoid collisions between the body and the rest of the environment. Participants often expressed amusement from being in the control of a different body verbally, usually in the first moment when seeing their avatar in the mirror. Three participants had balance issues during the stay in the VR when lifting feet from the floor.

4.5.3. Stimulation blinding

The stimulation mode was assessed correctly in the majority of sessions (80%), with a relatively low confidence (mean = 0.3, SD = 1.809) indicating that participants were rather guessing.

5. Discussion

We conducted a within-subject study investigating the effect of tDCS on embodiment in VR, while the responses were collected using both subjective (questionnaires) and objective (physiological recording of the EEG) methods. Considering the subjective differences, the brain stimulation had an effect with borderline statistical significance on the reported level of the SoA during the VR experience; the SoA towards the actions of the avatar was stronger in the sessions with anodal stimulation, compared to the sham-stimulation sessions.

Effect on the SoO was not present in our results. The tDCS applied over the rTPJ was expected to increase the self-identification with the avatar body due to the increased cortical excitability and consequent processing. Assumptions for the hypothesis of this study were based on the previous works focusing on both the sense of bodily ownership in context of the body ownership illusions (such as the RHI) and studies investigating the action self-recognition in various contexts, often in a social setting.

Nonetheless, despite their similarities, there are also major differences between the RHI experiment and the full-body virtual embodiment. Aside from the difference in sensory modalities engaged in the illusory effect, the RHI does not affect the unitary aspect of the bodily experience, only the specific body part is affected by the illusion (Blanke, 2012). Supposing the rTPJ performs detection of multisensory conflicts (Papeo et al., 2010), another reason for the inefficiency of the stimulation to alter the SoO might originate from the fact that there are no significant proprioceptive conflicts to be corrected during the virtual embodiment (if accurate tracking and rendering is assumed), contrary to the RHI incorporating proprioceptive mismatch between the real and the seen, rubber hand.

It would be tempting to hypothesize that reversal of the stimulation polarity (application of the cathodal stimulation to rTPJ area) would cause increase of the SoO due to disruptions in the rTPJ activity, causing erroneous body representation to be accepted as valid. Past research suggests this would not be the case, as previous attempts has rarely shown an inhibitory effect of the cathodal tDCS to the cognitive functions (Jacobson et al., 2012), even in case of the rTPJ stimulation and bodily self-recognition.

Aside from investigation into the effect of the stimulation, statistical testing investigating the neural correlates of the SoO component of the virtual embodiment was performed. Correlations between the SoO (mostly over the averaged sensorimotor channel set) and the theta band were found. Due to no SoO-related effects from the tDCS intervention, these results are purely correlational and further investigation needs to be performed to verify their validity. In the EEG study of VR embodiment performed by Pezzetta et al. (2018), increase in the power of theta oscillations was related to the detection of errors performed by the avatar. Such error-detection mechanism could be behind the relationship between the reported SoO towards the avatar body and the changes in theta oscillations observed in our study.

Main limitation of this study is the sample size. However, EEG and tDCS studies are commonly recruiting low number of participants due to the logistical limitations of the user testing using these methods. Within-subject design was utilized to increase the statistical power and alleviate this issue. It should be noted that the lack of stimulation effect on the subjective SoO was not borderline and there were no trends suggesting the SoO is strengthened following the stimulation. Second limitation could be the stimulation electrode positioning, as more accurate methods are sometimes used (such as using MRI or other neuronavigation techniques to precisely localize the area of interest in each participant). Nonetheless, for stimulation with the selected types of the electrodes, usage of the 10-20 system is considered acceptable (Herwig et al., 2003; Rich and Gillick, 2019).

The embodiment questionnaire subscale "Location" was composed of two questions with inverse scoring, first asking whether the user feels his/her body located where he/she sees the virtual body and the second was phrased "I felt out of my body". However, correlation between these questions was positively oriented ($r = 0.361$, $p = 0.118$), and after closely inspecting the data, it seems that there were two groups of participants. One interpreted a high "out of body" feeling as contradicting the "in avatar" (as expected), while the other interpreted it in congruence of "being in the avatar". Consequently, this embodiment subscale was excluded from the analysis.

6. Conclusions and Future work

This study investigated the effect of anodal tDCS to full-body virtual embodiment and the related changes in the EEG spectra. Stimulation did not produce the hypothesized effects on the SoO, but a weak effect (with borderline statistical significance) was observed on the reported SoA towards the avatar. Lack of the stimulation effect on the SoO could indicate general inefficiency of tDCS to enhance the sense of virtual embodiment, in contrast to the effects observed with partial body ownership illusions, such as the RHI.

Effect of the stimulation on the SoA in VR deserves further investigation, as it follows up on the past studies of the SoA outside VR. Mechanisms behind the SoA are still subject of hypotheses, and VR allows for unprecedented manipulations with both the substitute body and its surroundings, creating perfect conditions for the studies of human agency. Usage of the simple and inexpensive tDCS can further facilitate the SoA studies thanks to introducing of the causal relationship to the study design.

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