Examining and Enhancing the Illusory Touch Perception in Virtual Reality Using Non-Invasive Brain Stimulation

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ABSTRACT

Virtual reality (VR) can be immersive to such a degree that users sometimes report feeling tactile sensations based on visualization of the touch, without any actual physical contact. This effect is not only interesting for studies of human perception, but can also be leveraged to improve the quality of VR by evoking tactile sensations without usage of specialized equipment. The aim of this paper is to study brain processing of the illusory touch and its enhancement for purposes of exploitation in VR scene design. To amplify the illusory touch, transcranial direct current stimulation (tDCS) was used. Participants attended two sessions with blinded stimulation and interacted with a virtual ball using tracked hands in VR. The effects were studied using electroencephalography (EEG), that allowed us to examine stimulation-induced changes in processing of the illusory touch in the brain, as well as to identify its neural correlates. Results confirm enhanced processing of the illusory touch after the stimulation, and some of these changes were correlated to subjective rating of its magnitude.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *User studies*; *Empirical studies in HCI*;

KEYWORDS

Electroencephalography, Embodiment, Illusory Touch, Transcranial Direct Current Stimulation, Virtual Reality

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1 INTRODUCTION

Implementing touch into virtual reality (VR) is not always a straightforward task. VR scenes are mostly being perfected and examined in the visual domain, but engagement of other senses is also highly favorable for the design of immersive VR experiences. Classic approach to sense stimulation in VR consists of attaching a display to the relevant sensing organ [30]. Although this is effective for stimulation of vision and hearing (senses with relatively small sensing organs), it is much more difficult problem to stimulate the surface of the skin, the largest organ on the human body [8]. Recently, alternative approaches to haptic interfaces emerged, including electrical muscle stimulation [34, 35]. This paper investigates non-invasive stimulation of central nervous system, the brain, to facilitate synthetic tactile experiences.

VR offers rich possibilities for creation of environments and scenarios that are not feasible in the physical world. Sometimes being referred to as virtual un-reality [56], such VR scenes offer a unique opportunity for research in psychology and neuroscience. Although compelling delivery of tactile sensations would add to the overall utility of such VR scenarios, researchers can leverage even the current state, to study human behavior under conflicting somatosensory inputs. An interesting phenomenon occurs when users in VR are presented with a haptic event, but only in the visual form, when no actual touch is provided (e.g., when tracked virtual hands 'touch' a virtual object). Even though not experiencing any physical contact, users sometimes report 'feeling' the touch on the corresponding place on their body. This virtual illusory touch has not been studied yet, nor have been possibilities to induce it for purposes of tactile stimulation in VR.

One reason why this phenomenon occurs is the dominance of the visual perception over other senses – visual information can override the information coming from the other senses [23]. To a great degree, current VR systems, being predominantly visual, depend on this effect. The second reason for emergence of the illusory touch is the way how the human brain constructs bodily representation. Information from the senses are integrated in the brain to form plausible (internally consistent) representation of own body [24]. It has been revealed that the multisensory integration process can be manipulated to create altered perception of the self. One of the earliest experiments demonstrating malleability of the bodily representation is known as the rubber hand illusion [6]. In the rubber hand illusion, simultaneous haptic stimulation of a participant's hand (hidden behind a screen) and a rubber hand placed ahead of the participant (in a natural resting position) leads to rising of feelings that the rubber hand is actually part of the participant's body, and the tactile sensations seem to be originating in the rubber hand.

VR is an ideal playground for the body ownership illusions (see, e.g., [7, 51, 55, 61]). The current study leverages natural emergence of the sense of ownership and sense of agency in the virtual environments, i.e., feelings that the users own their virtual body or body parts and that they are the agents of actions of such virtual body. Using state-of-the-art VR (with a head-mounted display and accurate hand tracking), two VR scenes where participants experienced the illusory touch were created. In the active scene, participants actively touched a virtual object (ball) using their bare hands. On the contrary, the passive scene allowed participants to experience the illusory touch without actively moving their hands.

Manipulation of the illusory touch was performed using transcranial direct current stimulation (tDCS). This non-invasive brain stimulation technique has been used for clinical purposes as well as by hobbyists, with the main goal being usually enhancements in cognition and learning [17]. In this study, we examined processing of the illusory touch by the brain using evaluation of event-related potentials (ERPs), evoked by seeing the hand colliding with the virtual object. ERP analysis is a standard technique for analysis of electroencephalography (EEG) data, examining electrical brain response to a sensory, cognitive, or motor events [3].

Aim of this study is to examine enhancements of the ERPs previously identified as correlates of conscious tactile processing, after electrical stimulation of sensorimotor cortex corresponding to the dominant hand is applied. Secondly, we tried to examine if a link between the stimulation and subjective perception of the illusory touch exists. Each participant took part in two sessions of the experiment (one with the stimulation, one without stimulation, order was randomized), and two phases (active and passive scene) in each session. Session without the stimulation was blinded using sham-stimulation protocol (stimulation was set-up, but turned on for a very short amount of time only).

Results confirm presence of the illusory touch phenomenon. We identified ERPs that differ significantly between the stimulation and sham-stimulation sessions, while amplitudes of some of these ERPs are correlated with the subjective magnitude of the illusory touch. Our data suggest amplification of some of the ERP correlates of conscious tactile perception. Further investigation revealed stronger perception of the illusory touch in the second session of the experiment, regardless the tDCS mode of operation.

2 EEG, TACTILE IMAGERY AND CONSCIOUSNESS

Event-related potentials

EEG is a lightweight technology for non-invasive monitoring of ongoing brain activity with a high temporal precision. Desired number of EEG electrodes is placed on the participant's scalp and recorded simultaneously. The recorded signal consists of summation of electrical neuronal activity (specifically, neural discharges) from temporally and spatially congruent cortical neurons close to the recording electrode [60]. Thanks to the temporal acuity of EEG, time-locked evoked responses (the ERPs) to a sensory, cognitive, or motor events can be measured [3]. ERPs are surrounded by the ongoing oscillatory EEG activity, and their voltages are too weak to be interpreted from one recorded instance of the event. This is the reason why multiple recordings of a single stimulus is performed and averaged.

ERPs are usually evaluated as time-course of voltage change consisting of several peaks and valleys (positive- and negative-oriented voltage fluctuations), called ERP components [63]. Number of ERP components have been discovered and researched. One of the strongest (and well-known) ERPs is the P300, exploited for research in psychology, as well as for brain-computer interfacing purposes [57]. In the ERP nomenclature, P300 denotes a positively deflected voltage change occurring approximately 300 ms after the stimulus (event) onset. Similar nomenclature is used for other ERP components (N denotes negative deflection, C is used for ERPs with ambiguous deflection) [52, 57].

The early parts of the ERPs are usually dependent on the physiological properties of the stimulus – e.g. intensity (such as loudness or brightness). However, the later parts (starting approximately at 100 ms) were demonstrated to be dependent on the psychological variables of stimuli and influenced by their conscious processing [52]. Generation of the later ERP components (endogenous ERPs) is little dependent to completely independent on the physical stimulus that generated it.

Tactile consciousness and imagery

Pioneering work in the domain of ERPs related to the tactile stimuli, the somatosensory evoked potentials (SEPs), was done by Libet et al. (1967) [31]. They showed that following a tactile stimulus, evoked responses in parietal cortices (corresponding to the somatosensory cortex) can be detected and recorded using EEG. Interestingly, even sub-threshold intensity stimuli were accompanied by the evoked potentials. This led to the first discrimination between SEP components evoked by consciously attending the stimulus and those that do not depend on conscious perception. This discrimination was thoroughly studied by Schubert et al. (2006) [54], who confirmed that SEP components appearing before 100 ms mark (notably P60 and N80) in the contralateral somatosensory cortex were independent on the stimulus perception. On the other hand, amplitude of P100 and N140 components were enhanced with consciously perceived stimuli. P100 and N140 potentials were recorded from the frontal and parietal cortices, suggesting some degree of independence on processing by the somatosensory cortex, and rather suggesting cognitive processing of such stimuli.

This discrimination is of a great importance for research of the illusory touch. Although SEPs are the traditionally analyzed ERPs in studies of touch, there is no real haptic stimulation in our experiment. Our work, however, shares similarity to the tactile imagery and its consciously attended processing. Illusory touch in our case can be described as implicit tactile imagery facilitated by matching visual stimulus.

Conscious processing of a tactile stimulus is different from the conscious processing of other sensory modalities. In conclusion of their literature research on tactile consciousness, Gallace and Spence (2008) [18] claim that conscious perception of touch is inseparably dependent on the processing of more general (specifically, spatial) information in the brain. Tactile perception is largely dependent on the integration of information from multiple senses.

This is in line with the study discovering that observing a video with a hand being touched during the reception of tactile stimuli on own hand enhances the sensory threshold [53]. Moreover, just observing touch on other human body can be 'felt'. In [28], it was found that touch observation activates the somatosensory areas in the brain. Indeed, humans posses such 'tactile empathy' that allows them to experience illusory tactile sensations while seeing other persons being touched. Interestingly, this ability can become over-active in some individuals, resulting in visually-induced tactile synaesthesia [4].

Visually induced touch

Strongest enhancement of the tactile perception using visual cues is achieved when the touched object is perceived by the subject as his/her own body. This discovery was made thanks to the study that used the rubber hand illusion as a paradigm for manipulating different levels of body ownership [32]. Authors claim that the effect of visually enhanced touch is dependent on the perceived ownership of the hand. Perception of touch was enhanced by the visual stimulation significantly when the sensory stimuli were near the threshold.

The sensitivity to feel touch increases even after mere presentation of conflicting sensory cues – when the touch is seen, but no tactile stimulus is generated [49], thus in case coinciding with the experimental condition of this study. Finally, in the experiment with total of 220 participants, it was confirmed that a beam of laser light can be 'felt' on a fake hand [13]. This case was reported by 66% of 100 participants in the laser group – and not only tactile, but even thermal sensations were reported. Again, the rubber hand illusion set-up was exploited in this experiment.

Neural correlates of tactile imagery

As is the case in other sensory modalities, imagined touch produces significant neural correlates (in terms of neurophysiological signal in EEG and blood flow response in functional magnetic resonance imaging, fMRI). Tactile imagery was studied using EEG by Uhl et al. (1994) [58], who found the contralateral parietal cortex to be associated with processing of the tactile imagery. Their results were confirmed in another EEG study [16], examining the neural origins of imagery in visual, audial, and tactile domain. Finally, Yoo et al. (2003) [65] confirmed these findings using fMRI as well, observing mainly activations of contralateral somatosensory cortices during the tactile imagery, together with activations in the left parietal lobe.

These findings were leveraged for selection of the scalp positions for the EEG electrodes and ERP components in this study, and were also taken into account while planning the electrode montage for the purposes of stimulation. Literature review of tDCS studies focused on the motor or somatosensory enhancement is provided in the next section.

3 NON-INVASIVE ELECTRICAL BRAIN STIMULATION

Electrical brain stimulation with tDCS causes sub-threshold changes to the resting membrane potential of the affected neurons, leading to changes in cortical excitability and activity [47]. In practice, the resting state of neurons in the stimulated region is affected, and the neurons then communicate more or less likely. Stimulation using anode as the active electrode leads to increases in neuronal firing, while cathodal stimulation attenuates the neural communication [64].

Two electrodes must be set up for tDCS. Correct positioning of the active and return electrode is crucial to achieve the desired effects. Nitsche and Paulus (2000) [44] experimented with various scalp locations for the active and return electrode for experiments including hand motor cortex. Optimal anode location was found to be over the hand motor cortex location (C3/C4 positions according to the international 10-20 EEG electrode placement system [27]) and the return electrode location should be placed over the contralateral supraorbital location (corresponds to the AF4/3 locations; see Figure 1). Evaluation using transcranial magnetic stimulation showed an increased cortical excitability by up to 40%. Later, the same authors studied relation of the stimulation length to the length of its effects [45]. Following 5- and 7-minute long tDCS session, the increased motor responses returned to the baseline after couple of minutes; using 9- to 13-minute long stimulation, the effect lasted for up to 1.5 hours. Current of 1 mA was delivered during the stimulation in these studies, and 1-2 mA are typical currents in the studies using tDCS [64].

Both anodal and cathodal tDCS stimulation of the hand motor cortex was studied in the last two decades. Participants (N = 34) receiving anodal stimulation showed improved motor learning [46]. Increases in the motor function of the non-dominant hand after 20 minute anodal stimulation was achieved [5]. Interestingly, this effect was not reached in the dominant hands of the participants. Tactile perception abilities were decreased after cathodal tDCS stimulation (7-minute, 1 mA) [50] (anodal stimulation did not increase the tactile perception in this study). Cathodal tDCS was studied even for acute pain perception [1]. Subjective pain rating scores and N100, N200, and P200 components were evaluated after acute painful stimulation of the hand. Contralateral N200 component and subjective pain perception showed to be decreased in the experiment, with no effect of anodal and sham conditions. Similar results were obtained later for cold detection threshold [21].

SEPs elicited by electrical stimulation of the right median nerve (peripheral nerve stimulation was used to elicit SEPs rather than physical manipulation with the arm) significantly increased after anodal tDCS in the work of Matsunaga et al. (2004) [37]. Cathodal tDCS did not have an effect on SEPs. The effect lasted for 1 hour after 10-minute stimulation with 1 mA. Using fMRI, altered response to the tactile stimulation of foot after anodal tDCS was confirmed in terms of the hemodynamic response [62]. In 2014, a meta-analysis study on the sensory and pain perception changes following anodal tDCS was conducted [59], concluding that anodal tDCS of the primary motor cortex increases pain and sensory threshold in healthy individuals. However, the authors acknowledge the number of participants was low in some of the analyzed studies and warn the readers before interpreting the results.

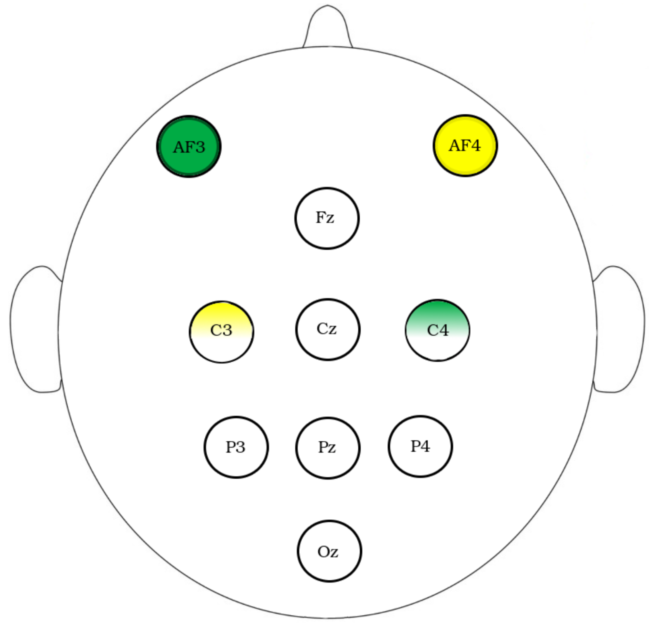
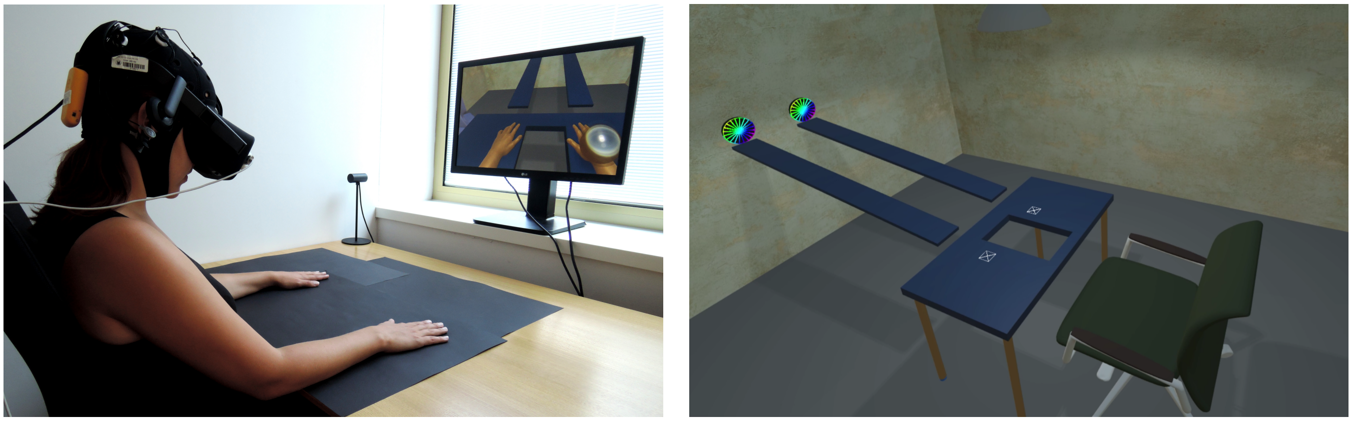


Figure 1: EEG and tDCS channel set-up. All the channels except for AF3 and AF4 were used for the EEG recording (white and semi-white background). For right hand stimulation, C3 was the anode and AF4 the return electrode (yellow). For left hand stimulation, C4 was the anode and AF3 the return electrode (green).

4 METHODOLOGY

This experiment was conducted in a within-subject design with the stimulation being performed blindly in one of the two sessions. Sham stimulation was used in the session without the stimulation, so the participants did not know when the stimulation was actually performed. In the sham session, stimulation was turned on for very short amount of time that does not produce any changes in the brain. A questionnaire was used to assess the number of cases when participants guessed or recognized the stimulation mode. Participants were also blind to which hand's motor cortex was stimulated. They were however informed that purpose of the study is to measure the influence of tDCS on the illusory touch. All the participants gave their informed consent using document that included basic principle and common uses of tDCS and further information about the study. The study was approved by the local ethical committee with a reference number EKV-2018-078.

Total of 10 participants was employed for the study, all between 24-31 year of age (median 27, SD = 2.539). Both sessions took place on different days within 3 days. Order of the sessions (stimulation and non-stimulation session) was randomized throughout the study (the number of participants stimulated on the first session is equal to the number



(a) Participant in the passive phase of the experiment.

(b) Overview of the virtual scene.

Figure 2: Experimental setting and the experimental VR scene.

of participants without stimulation on the first session). Four female and six male participants participated in the study.

Virtual scene design and delivery

Head-mounted display (HMD) Oculus Rift CV1 (resolution 1080x1200 per eye, 90 Hz refresh rate, 110° field of view, rotational and positional tracking) [2] was used for the presentation of the VR scene, together with HMD-mounted Leap Motion [38] to track participants' hands. To maximize the accuracy of Leap Motion, light was dimmed in the room, and the desktop under participant's hands was covered with black paper sheets.

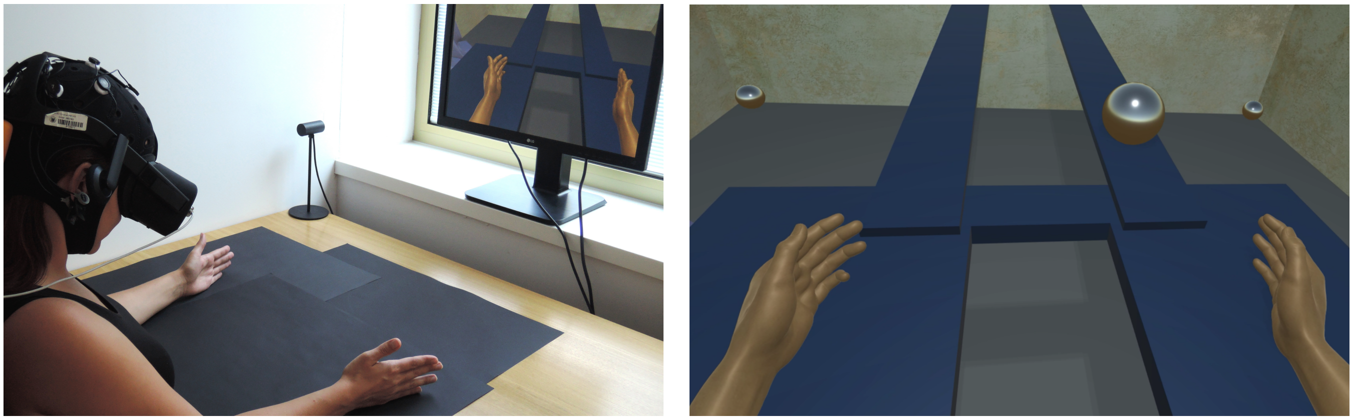
The virtual scene had a form of a closed room, the participants sat roughly in the middle of the room by a desk. Overview of the scene is present in Figure 2. Two ramps were mounted from the front wall, with their ends positioned at the desk before the participant. Silver balls approx. 10 cm in diameter were arriving towards the participant alternatively from the right and left ramp. Active phase of the experiment required the participants to actively push the ball towards the center of desk, where a hole was created to let the balls escape the desktop space. In the passive scene, participants only rested their hands by the ends of the ramps and watched the ball to hit and run over their hands. The scene was developed using Unity version 2017.3.0f3, for the representation of hands, the realistically looking hand models 'Pepper Hands' from Leap Motion suite were used (visible in Figure 3). The hands do not posses any stereotypical male or female characteristics, thus could be considered as androgynous hands.

Total number of collisions was 20 for each hand per condition per session, resulting in total of 160 recorded ERPs per participant. This number allows analyzing the ERPs without having overly long sessions, as the results could be influenced by dropping levels of attention. Inter-stimulus interval was 7 seconds in the active phase and 5.5 seconds in the passive phase. The pace of the active phase was slower in comparison to the passive one, as the participants had to actively engage in the hand-ball collision (i.e., find the moment of collision in space and time, prepare the hand movement, execute the movement). In case the collision did not happen for a specific trial, the trial was repeated (the ball approached participant at the same hand). Participants were informed about this behavior, the reason for it was to record sufficient number of ERPs in case that participant misses the ball, or due to the technical issues in hand tracking.

Stimulation

We used Neuroelectrics Starstim 8 [42] for the tDCS. Stimulation was performed using a pair of saline-soaked circular sponge electrodes with the area of 25 cm^2. Anode was placed at the motor cortex of the dominant hand, at C3/C4 electrode (according to the 10-20 international system) contralateral to the dominant hand (the dominant hand was assessed using questionnaire). Cathode was placed on the forehead (AF7/8 position) ipsilateral to the dominant hand, contralateral to the anode (see Figure 1)[1]. Stimulation took 15 minutes with 3 seconds ramp-up and ramp-down (ramp-up and ramp-down denotes the time to reach the full stimulation power in the beginning of the process and vice versa), stimulating current was 1 mA. Parameters of the stimulation are based on previous studies [15, 37, 44, 45, 50], Section 3 provides more details. The sham protocol consisted of 3 seconds of ramp-up and ramp-down only, the rest of the set-up being the same as in the stimulation sessions, to not compromise the

[1]90% of the participants were right-handed; right-handed set-up was anode at C3, cathode at AF8



(a) Participant in the active phase of the experiment.

(b) First-person view on the scene in the active phase of the experiment.

Figure 3: Active phase of the experiment.

blinding. In both sessions, electrodes for both dominant and non-dominant hand were positioned into the cap, so the participants could not make any deductions regarding the stimulation set-up.

The somatosensory cortex of hands is neighboring the primary motor cortex controlling the hand. Following the protocol from the previous studies, it was decided to stimulate the C3/C4 scalp location, corresponding to the motor cortex, rather than the somatosensory cortex of a hand. However, the selected electrode type for tDCS probably effectively contributed to both cortices in the stimulation process (similarly to the previous studies).

EEG

EEG data were collected using Neuroelectrics Enobio 32 [41] at 500 Hz sampling frequency, using 8 electrodes, mostly concerning the motor and somatosensory cortex (C3, P3, Fz, Cz, Pz, Oz, C4, P4). NG Geltrode [40] AgCl electrodes were used, referencing was done using a Common Mode Sense/Driven Right Leg (CMS/DRL) earclip. Impedance check was done using Neuroelectrics stock application, following the recording using Openvibe 2.1.0 [48]. Markers (exact moment of the hand-ball collision) were triggered from the experimental application using TCP connection to Openvibe acquisition server. Markers were saved together with the EEG data for the analyses purposes. EEG recording performed concurrently with the usage of HMD has been proven to be feasible before, even for purposes of the ERP analysis (see [22]).

Experimental design and participants

Procedure

Upon being invited to the room, participants were introduced to the experiment using an introductory document accompanying the consent form, and any questions not compromising the blinding were answered before the experiment started. They filled-in a short pre-experiment questionnaire assessing their interest, mood, and fear from the experiment. Stimulation device set-up followed (impedance check took approximately 2-10 minutes, depending on the participant's scalp conductivity), and either sham or stimulation protocol took place for 15 minutes. After the stimulation, the elastic cap with stimulation electrodes was replaced by a cap with the EEG electrodes. The caps were of the same type, as both stimulation and EEG recording were done using systems from the same company. Impedance check was performed again, as different number, location, and types of electrodes were used, taking approx. 5-15 minutes.

Detailed instructions for the experiment followed. For the active phase (displayed in Figure 3), participants were instructed to place their hands on the physical desk (which coincided with the VR desk) on their little fingers to comfortably hit the balls towards the middle of the desk, into the hole. HMD was mounted on participant's head, and a short demo took place (before the actual recording phase started), so the participants can be familiarized with the environment. Active phase took always the first place, mainly to increase the embodiment effect using visuo-motor synchrony (requiring an active interaction). This phase took 6-7 minutes. Passive phase (displayed in Figure 2) consisted of just resting the hands on the desk, paying attention to the collision of the balls with the hands. The passive phase had an approximate duration 4.5 minutes and was not preceded by a demo. There was no rest phase between the phases (HMD was worn continually, the time required to switch the scenes was about 1 minute). After both phases took place, HMD and EEG cap were removed, and participants were asked to fill-in post-experiment questionnaire (quantitative and open qualitative part). Total duration of the experiment did not exceed 60 minutes.

Besides being given instructions regarding the interaction inside the VR scene, participants were also informed about bodily movement limitations during the EEG recording. Eye movements and blinking should have been limited, especially during the collision of the ball and the hand. For that purpose, we instructed participants to shift the gaze from the hand (experiencing last collision) to the other hand soon after the collision took place (for that purpose, the ball approached the hands in alternative manner). After that, they were instructed to keep their gaze fixed on the hand, and not to follow the incoming ball. Before each phase, participants were reminded to try to be focused and conscious about the task.

5 EVALUATION

EEG data pre-processing and ERP analysis

EEGLAB [10] was used for the ERP analysis. In the preprocessing phase, all the recordings were re-sampled to 250 Hz, filtered using high-pass filter at 1 Hz (cut-off 0.5 Hz), and low-passed at 30 Hz. The next phase consisted of cleaning using artifact subspace reconstruction (ASR) algorithm [29]. Cleaned data were normalized using z-score and cut into epochs beginning 1 second pre-stimulus to 0.45 second post-stimulus. Mean values of the epoched data were removed using MATLAB *detrend* function. Manual artifact removal was then performed on the epoched data. None of the subjects was rejected from the study, but channel Cz was not used in the analysis for the reasons of poor signal-to-noise ratio.

ERP plots were generated using EEGLAB *std_erpplot* function, with time limits -110 to 450 ms around the stimulus onset, and with baseline removal from -110 to -10 ms before the stimulus. The reason to set the baseline removal period to 10 ms pre-stimulus was to limit the impact of motor action on the generated ERP in the active phase (similar as in the study [54]). Time-courses of ERP for each of the following combinations of conditions (stimulated x non-stimulated) and (passive x active) were generated for the dominant hand. Moreover, for the stimulation condition, ERPs for the left hands were extracted as well.

Besides the original ERP components that were to be studied (P100, N140, P300), additional components of interest were identified based on the grand average ERP plots with marked significant differences (generated using EEGLAB). Additional components that were examined are N100 and P200. The ERP components were measured using temporal window where average voltage was calculated (as recommended in [36, 63]). Time windows were assessed based on previous studies, with the following timings being used: 70-130 ms (P100), 90-170 ms (N100), 120-160 ms (N140), 180-230 ms (P200), and 250-400 ms (P300). Lateralized EEG channels (C3, C4, P3, P4) were not inverted in the evaluation of the one left-handed participant.

Questionnaires

Two questionnaires were used; pre-experiment and post-experiment questionnaire, both consisting mostly of quantitative questions answered on a 7-point Likert scale (with steps ranging from 0='Not at all', 4='Somewhat', to 7='Completely'). Pre-experiment questionnaire served to assess the mood, interest in the experiment, and fear from the stimulation and VR. This questionnaire was based on Questionnaire for Current Motivation (based on the translation from [43]). Purpose of the post-experiment questionnaire was measuring participant's subjective sense of ownership (SoO), sense of agency (SoA), loss of hands (LoH), and affect in the virtual scene (based on Longo's et al. psychometric approach to embodiment [33]), and also to collect information regarding the illusory touch. All questionnaires were translated to Czech language.

Investigation concerning the illusory touch was performed using a pair of questions 'During the VR scene, it seemed as if I felt the touch on my own hand when I purposely touched the virtual ball with one of my hands' and 'During the VR scene, it seemed as if I felt the touch on my own hand when the ball touched one of my hands'. Moreover, participants were asked to balance the magnitude of the illusory touch between left and right hand on range from -3 to +3 (the same scale as the rest of the questions), if they perceived the illusory touch stronger in left or right hand (for the one left-handed participant, the scale was inverted in the evaluation).

Post-experiment questionnaire also asked the participants whether they think the stimulation was used during the session (yes/no answer), and it contained an open qualitative part asking the participants to provide us with any thoughts, comments, or feelings regarding the experimental session.

Statistical testing

Correlations in the data were evaluated using Spearman correlation test, within-group differences were computed using Wilcoxon signed-rank test. Statistical tests were performed using IBM SPSS version 24. To evaluate correlations in the dataset, data from questionnaires were paired with the corresponding ERP values regardless the condition (stimulated/non-stimulated), resulting in number of cases N = 20.

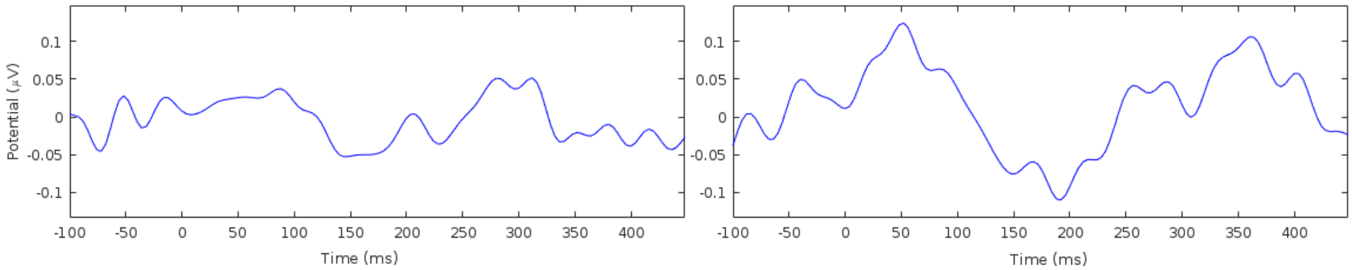


Figure 4: Grand-averaged ERPs for the dominant hand at electrode location Pz, passive condition. Left plot – non-stimulated, right plot – stimulated. To generate these plots, data were cleaned with higher high-pass filter setting (cut-off 2.5 Hz) than for the analysis purposes. Enhanced N140 and P100 are visible at these plots, as well as stronger P300 in the stimulated condition.

6 RESULTS

Effect of stimulation on the illusory touch perception

Within-subject test of differences between the stimulated/non-stimulated conditions ERPs, generated by the illusory touch produced by the dominant hand, revealed several potentials being significantly amplified or reduced following the stimulation. To further validate the effect of stimulation, the differences between the left and right hand in the stimulation session were tested as well.

N140. The strongest effect was observed on the amplitude of the N140 potential. N140 potential was amplified (more negative) at electrode location Fz (Z = -2.599, p = 0.009) in the passive phase, and P3 (Z = -2.090, p = 0.037) in the active phase of the experiment. Statistical testing of differences between the dominant and non-dominant hand in the stimulation session confirms amplified N140 for the dominant (stimulated) hand at P3, with non-significant trends both in the active phase (Z = -1.836, p = 0.066) and in the passive phase (Z = -1.718, p = 0.086).

P200. Effect of P200 attenuation was apparent at multiple EEG recording locations. Strongest effect was observed in the active phase at the site Pz (Z = -2.293, p = 0.022) and at P4 (Z = -1.988, p = 0.047), and with a borderline significance at P3 (Z = -1.886, p = 0.059). P200 was reduced in the passive phase at electrode C3 (Z = -2.090, p = 0.037).

P100. Amplitude of P100 was significantly weaker contralateraly to the stimulated hand, at channel P4 in the active phase (Z = -2.803, p = 0.005). In the active condition, the P100 at P4 was non-significantly weaker for the dominant hand as compared to the non-dominant hand (Z = -1.836, p = 0.066). Reduced P100 in the passive phase was observed at Fz with a borderline significance (Z = -1.886, p = 0.059). Amplitude of the P100 potential was enhanced at the Pz electrode in the passive condition (visible in Figure 4), but this effect was not statistically significant.

Other ERPs. Amplitude of the P300 potential tended to be stronger in the tDCS condition in multiple channels, but this effect was not found significant. The P300 enhancements were mainly seen in the passive phase (see Figure 4), as the passive phase hand-ball collisions elicited distinct P300, contrary to the active phase.

Neural signatures of illusory touch

Correlation analysis of the ERPs with the questionnaires was performed in order to reveal links between the subjective magnitude of the illusory touch and its EEG signatures.

The strongest effect was observed for the N140 potential at P3 location in the passive condition (r = -0.597, p = 0.005, negative correlation means that the stronger feeling of illusory touch was coupled with the enhanced N140 amplitude). This effect was, however, cross-conditional; i.e. enhancement of the N140 at P3 in active condition was coupled with the subjective evaluation of the illusory touch in the passive condition. Direct effect was observed for reduction of the P100 amplitude (r = -0.580, p = 0.007) and enhancement of N140 amplitude (r = -0.495, p = 0.027), both at P3.

Active phase illusory touch self-evaluation was positively correlated with the P100 amplitude at Pz location. Directly, the effect is observed with r = 0.445, p = 0.049. Correlation with the passive phase amplitudes were present as well, also in P100 at Pz, with r = 0.490, p = 0.028.

Questionnaire evaluation

Illusory touch was evaluated using a 7-point scale in the questionnaire, for the active and passive phase separately. Median values for the active and passive phase, respectively, were 3 (SD = 1.780) and 4 (SD = 1.970), minimal and maximal values 1 and 6 for both phases. This confirms that the users indeed felt a touch-like sensation during the VR experience. Further statistical testing did not confirm that the stimulation using tDCS has an effect on the perception of illusory touch (Z = -1.190, p = 0.234 in the active and Z = -0.105, p = 0.916 in the passive phase). Results of the left/right hand balance of the illusory touch are not in favor of increased dominant hand sensitivity (median = 0, SD = 1.191).

On the other hand, an effect of the session number to the illusory touch perception was revealed. This effect was significant in the passive phase (Z = -2.214, p = 0.027), and not significant in the active phase (Z = -1.730, p = 0.084). However, most importantly, the perceived illusory touch was stronger in the second session in both phases. Median difference was one point on the scale in the active phase, and three points in the passive phase.

Participants maintained high SoO and SoA during the VR experience. Median SoO is 5.1 and SoA 7. LoH median is 2.25. Median values for pre-experimental screening questions are as follows; interest: 7, fear: 1, mood: 6. Similarly, questions aiming at monitoring affect after the session have median answers equal to 7. None of these questions had answers significantly different between the stimulation and non-stimulation session, or between the first and second session.

According to the questionnaires, blinding of the tDCS was successful, with 55% of cases when the participant guessed or recognized whether the stimulation was used, or sham stimulation took place.

7 DISCUSSION

This study examined the illusory touch phenomenon in VR. Perception of conflicting multisensory stimuli was examined, specifically the perception of visually presented touch in the absence of real tactile stimulus was studied in the VR setting. Most importantly, the effect of non-invasive brain stimulation on perception of illusory tactile sensations was investigated for the first time.

The link between an enhanced amplitude of the N140 and P100 ERPs and self-evaluation of illusory touch magnitude was identified. It was previously identified that these potentials are influenced by the level of attention paid on the relevant stimulus. Consciousness requires attention [9], especially in case of the conscious tactile perception (see Section 2). Even during the experience of a real touch, the sensitivity and spatial localization is dependent on the information coming from the visual channel. Level of attention during observation of the visualized, illusory touch has major role on its perception.

Participants in the present study were instructed to keep being focused on the task, particularly during the moment of the contact between the virtual hand and ball. The standard protocol for ERP recordings requires many repetitions of the same event, and it is therefore likely that the level of attention decreased during the course of the experiment. This ‘extinction’ of potentials due to varying levels of attention has been described before [54] and can account for statistically weaker effect. In theory, coupling the ERP recordings with assessment of attention levels using oscillatory EEG data together with a higher number of participants could reduce likelihood of this effect.

Different mechanisms have been found to be responsible for the modulation of P100 and N140 potentials during conscious perception of tactile stimuli. Origin of P100 is the posterior parietal cortex, and its purpose seems to be spatial organization of the haptic stimuli [11, 54]. The following N140 is localized more frontally and represents higher level perception, such as evaluation of relationship between objects in space [11]. Both of these potentials were correlated with the illusory touch magnitude, but P100 was weaker in the tDCS sessions. However, P100 reduction was seen frontally and over parietal cortex corresponding to the non-stimulated hand. Parietal P100 enhancement was positively correlated with the active condition illusory touch rating by participants.

It remains to explain the negative correlation between the passive condition illusory touch rating and the P100 amplitude over the contralateral parietal cortex. Some answers can be provided by findings in a paper on touch-related potentials during concurrent visual task [26]. In their case, the somatosensory P100 was suppressed during the visual task. Passive phase in our experiment consisted of a visual task only, and so it is likely that the P100 enhancement did not occur, contrary to the case of the active phase. Interestingly, the P100 reduction seems to be even inversely related to the illusory touch magnitude. In another study, examining multimodal stimulus integration [12], the P100 amplitude (in their case, bilaterally distributed) was the weakest when the tactile stimuli did not match its visual response. Reflection of such mismatch might be reflected by the P100 amplitude reduction in our experiment. Moreover, in [12], N140 was monitored during a conflicting bi-modal stimulus presentation. The N140 amplitude was enhanced when the participants had to monitor visual and tactile inputs simultaneously, but not when participants responded to visual stimuli only and the tactile stimuli were irrelevant, suggesting that tactile processing is influenced by vision when the visual stimulus is somehow relevant to the tactile one.

Low number of electrodes does not allow to conduct an ERP analysis with respect to the scalp distribution of the potentials with high precision. This is necessary to study in the future. Extraction of the precise timings of the illusory touch events is not straightforward. The exact moment of the hand-ball collision was chosen as the event for the studied ERPs. Nevertheless, this moment can be perceived at different times across the participant population. Especially in the active paradigm, participant observation showed that some participants are not able to accurately deduce the moment when the ball arrives near the hand, despite realistic physics used in the VR scene. Most participants improved eventually, after multiple trials were finished. ERP analysis requires precise timing of the event, and in the case of this study, the event was not in fact real somatosensory stimulus, rather its subjective interpretation (imagery), based on a visual substitution.

Promising evidence considering ERP differences in the brain processing of the illusory touch following tDCS was found, and some of these potentials were indeed correlated to the subjective experience of the phenomenon. According to the questionnaires, participants felt the illusory touch stronger in the second session, regardless the stimulation was turned on in the first or second session. Analysis of questionnaire differences between the stimulation and sham-stimulation sessions did not reveal a direct link between tDCS and the subjective magnitude of the illusory touch. According to this result, it seems that tDCS does not increase the subjective feelings connected to the illusory touch. Nevertheless, the low number of participants must be kept in mind before interpreting the results, as well as the possibility of yielding different results with a different tDCS setup. Assessment of such a subjective phenomenon is difficult, and the use of questionnaires has many drawbacks. Participants in this study rated the illusory touch strength with high variation and had rather 'learned' to feel the illusory touch, as indicated by overall higher rating in the second session (statistical testing was used to confirm that these stronger illusory touch ratings were not conditioned by the participants believing that the stimulation was used in the second session).

This study attempted to substitute the tactile perception with a visual stimulation. As presented in the introduction of this paper, exploiting imperfect multisensory integration process in humans to create body ownership or presence illusions is not uncommon. VR environment gives an illusion of 'being' the avatar, as well as the illusion of presence in the VR scene. It has been demonstrated (see Section 2) that tactile perception is heavily dependent on integration of the spatial information, making it a perfect sense for illusory manipulation. But it is important to note that even other, more common VR experiences are just sensory illusions. In VR, accurate stimulation of users' vision can make them believe that movement is perceived. Unwanted side effects may appear with this sensory mismatch, such as vection. Still, if used carefully, users in VR can perceive self-movement despite lack of the corresponding sensual (vestibular) stimulation.

8 CONCLUSION AND FUTURE WORK

This study confirms that tDCS has effects on the brain processing of the illusory touch. It opens a new chapter of tactile perception facilitation using the brain stimulation. This is an important topic for the future of VR, and this study presents results suggesting it should be investigated further. The results do not confirm subjective enhancement of the illusory touch following the tDCS. Significant differences between the experimental conditions were found in terms of ERPs.

Our stimulation set-up was built upon the practices from the past studies, and quantitative parameters such as the length and intensity of the stimulation procedure are most likely sufficient to produce distinct effect. However, it is important to bear in mind that different results can be gathered with a different localization of the stimulation electrodes. In the future, other tDCS montages should be investigated. Firstly, an experiment investigating reduction of the illusory touch magnitude following cathodal stimulation can be conducted. Investigation to the changes of subjective illusory touch magnitude following anodal stimulation of the non-dominant hand might be interesting (in line with [5]). Finally, a tDCS electrode montage leading to subjectively perceivable effect of enhanced illusory touch may be found.

Computer-brain interaction is still not very common (apart from neuroprostheses) [19], mainly because the understanding of the human brain structure and function is very crude. Another stimulation technique promising facilitation of VR tactile experiences is transcranial alternate current stimulation (tACS). Whereas tDCS is used to manipulate the resting membrane potentials to increase or decrease neuronal firing threshold, tACS is used to interfere with the ongoing neural activity [25], opening the possibility to create a real-time computer-brain communication channel. Based on the results from studies with rodents, synthetic haptic perception can be facilitated with tACS [39].

Main issue with non-invasive brain stimulation is low spatial resolution (the signal needs to cross the skull and other layers before reaching the brain). When spatial acuity of the transcranial stimulation improves, closed-loop tACS stimulation could be used to deliver synthetic tactile sensations to users in the future. Research in non-invasive brain stimulation is currently looking for a more focused, even deep-brain stimulation using scalp electrodes [14, 20].

An interesting result of this study suggests enhancement of the illusory touch phenomenon in the second VR session. It seems likely that the participants became habituated to the expected outcome of the task, i.e., 'feeling' the touch with their hands. Although strengthening of the illusory effect with time is not unexpected, the curious outcome of our experiment is strengthening of the illusory touch effect between two experimental sessions on two different days. This effect makes sense in the context of habituation to the VR experience. Developers of VR scenes can leverage this finding for creation of experiences that gradually trick the human perception into greater depths, creating illusion of multisensory experiences using just the basic interaction tools.

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