ABSTRACT
Redirected walking (RDW) enables virtual reality (VR) users to explore large virtual environments (VE) in confined tracking spaces by guiding users on different paths in the real world than in the VE. However, so far, spaces larger than typical room-scale setups of 5m × 5m are still required to allow infinitely straight walking, i.e., to prevent a subjective mismatch between real and virtual paths. This mismatch could in theory be reduced by interacting with the underlying brain activity. Transcranial direct-current stimulation (tDCS) presents a simply method able to modify ongoing cortical activity and excitability levels. Hence, this approach provides enormous potential to widen detection thresholds for RDW, and consequently reduce the above mentioned space requirements. In this paper, we conducted a psychophysical experiment using tDCS to evaluate detection thresholds for RDW gains. In the stimulation condition 1.25 mA cathodal tDCS were applied over the prefrontal cortex (AF4 with Pz for the return current) for 20 minutes. TDCS failed to exert a significant overall effect on detection thresholds. However, for the highest gain only, path deviance was significantly modified by tDCS. In addition, subjectively reported disorientation was significantly lower during the tDCS as compared to the sham condition. Along the same line, oculomotor cyber sickness symptoms after the session were significantly decreased compared to baseline in tDCS, while there was no significant effect in sham. This work presents a simply method able to modify ongoing cortical activity and excitability levels. Hence, this approach provides enormous potential to widen detection thresholds for RDW, and consequently reduce the above mentioned space requirements.

CCS CONCEPTS
• Computing methodologies → Virtual reality; • Human-centered computing → Virtual reality.

KEYWORDS
virtual reality, locomotion, redirected walking

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1 INTRODUCTION
Virtual reality (VR) denotes the technology to fully immerse a user into a virtual environment (VE), which is usually done by using head-mounted displays (HMDs) in combination with 3d tracking systems for position and orientation. Such setups are able to produce a sense of presence in the user, i.e., so-called place illusion and plausibility illusion [Slater 2009].

Locomotion is an important activity in such VEs to support the user’s sense of being present [Usoh et al. 1999a]. While purely virtual locomotion techniques like teleportation exist [Bozgeyikli et al. 2016], it is beneficial to leverage bipedal human walking since it is generally considered to be the most natural and common locomotion technique in the physical world [Steinicke et al. 2013] and the most presence-enhancing form of locomotion in VR [Usoh et al. 1999a]. Basic implementations of real walking can be realized by using a tracking system to map position and orientation of a user’s tracked head one-to-one to a virtual camera. Then, a one meter forward movement in the physical world is mapped to a one meter forward movement in the VE. This provides the user with near-natural sensory feedback similar to the physical world but reduces the accessible space in the VE to the size of the physical tracking space. An interesting technique which aims to break these restrictions is redirected walking (RDW) [Nilsson et al. 2018; Razzaque et al. 2001]. RDW is inspired by findings from the field of perceptive psychology and guides the user on a different path in the real world than she travels in the VE without being able to detect this difference. For instance, a straight virtual path can be bent so that the user walks a curved arch in the real world. However, there are still some limitations when using this technique. For example, an area of approximately 24m × 24m in the physical world is necessary to allow users to walk on an infinite straight path in the VE while they are being redirected on a circular path in the real world [Grechkin et al. 2016]. For smaller spaces, users might be able to detect this manipulation of their pathway reliably, i.e., the visual-vestibular conflict gets too obvious, which might lead to lowered presence as well as increased cyber sickness.
However, it has been a long-term vision to create more realistic experiences by connecting VR directly to the brain. This way, thoughts of the user could be read without detours and leveraged to control the VR system or manipulate the virtual world. Through so-called Brain-Computer Interfaces (BCI), VR could become a more natural experience for users, with the potential to significantly impact a variety of fields ranging from video games to medicine. Advances in machine learning and BCI combined with the development of inexpensive wearable sensors has made practical the interaction of users with computers and mobile devices through brain electroencephalography (EEG) signals [Tan and Nijholt 2010; Wolpaw et al. 2002]. This is already moving quickly to become widely available as the sensor technology is becoming more economical. Also there exists some steps of using BCI for VR [Bayliss and Ballard 2000; Lécuyer et al. 2008]. The intersection of these two technologies, VR and BCI, is the topic of this survey paper. While but EEG denotes the ability to read electrical activity of the brain, we present a method to write to the human brain, i.e., to use electrical signals to stimulate the activity of the brain.

In this context, transcranial direct current stimulation (tDCS) is meanwhile a widely employed technique to modify cortical excitability and activity. The underlying concept of applying such relatively weak currents to the scalp is that it can facilitate or suppress ongoing neuronal activity without affecting non-active neuronal networks [Stagg et al. 2018]. To the best of our knowledge, tDCS has not been applied to RDW so far. Since it was shown that the cognitive activity underlying RDW can interact with cognitive abilities required for working memory [Bruder et al. 2015] and both, egocentric as well as allocentric, reference systems of spatial navigation are presumably involved in RDW, we aimed to apply tDCS in such a way as affect these brain functions. The goal was to achieve positive effects on RDW performance, i.e., to enlarge the walkable VE and improve the overall VR experience. Our hypothesis is that tDCS can lower the abilities of spatial cognition and, therefore, higher redirection gains might be applied without being consciously perceived by the user. This would lead to wider detection thresholds and a reduction of the space requirements for unlimited walking in VR. Moreover, this stimulation might also have an effect on cyber sickness and the sense of presence in VR.

The remainder of this paper is structured as follows. Section 2 discusses background information on RDW and tDCS. Section 3 presents the experimental procedure and methods on tDCS application during RDW in VR. Section 4 discusses our findings. Section 5 concludes the paper and gives an outlook on future work.

2 BACKGROUND

In this section, the fundamentals of RDW and our stimulation approach are presented.

2.1 Redirected Walking

A large body of literature has been published on the topic of RDW since it has been introduced in 2001 [Razzaque et al. 2001]. Several authors presented review articles [Bruder et al. 2013; Langbehn and Steinicke 2018; Nilsson et al. 2018] and taxonomies [Suma et al. 2012]. Steinicke et al. introduced gains to describe differences between real and virtual motions in RDW [Steinicke et al. 2010], i.e., ratios between a user’s movements (translations and rotations) in the real world and in the virtual environment. For instance, rotation gains $g_R$ are defined as the quotient of the considered component of a virtual rotation $R_{\text{virtual}}$ and the real-world rotation $R_{\text{real}}$, i.e.,

$$g_R := \frac{R_{\text{virtual}}}{R_{\text{real}}}.$$  

When a rotation gain $g_R$ is applied to a real-world head rotation with angle $a$, the virtual camera is rotated by $\alpha \cdot g_R$ instead of $a$. This means that if $g_R = 1$ the virtual camera rotation matches the head rotation. In the case $g_R > 1$ the virtual camera appears to rotate more than the head, whereas a gain $g_R < 1$ causes the virtual camera to rotate less. In a similar way, translation gains $g_T$ are defined as the quotient of virtual camera translations $T_{\text{virtual}}$ and the tracked real-world head translation $T_{\text{real}}$, i.e.,

$$g_T := \frac{T_{\text{virtual}}}{T_{\text{real}}}.$$  

Moreover, curvature gains $g_C := \frac{r}{\bar{r}}$ are defined by the radius $r$ of the circular path in the real world onto which users are redirected while walking a straight path in the VE. Langbehn et al. extended these with bending gains, which incorporate the bending of a virtual curve as well. Let this curve in the VE be part of a circle with the radius $r_{\text{virtual}}$, bending gains are specified by $g_B := B \cdot g_C \cdot r_{\text{virtual}}$. Multiple researchers identified detection thresholds for these gains in psychophysical experiments. These thresholds indicate just-noticeable differences between vision and the vestibular and proprioceptive sensory channels. In order to determine detection thresholds for path curvature, users walked a straight path in the VE, which was bent by a curvature gain either to the left or to the right in the real world. Users had to judge if the physical path was bent left or right in a two-alternative forced-choice task. According to Steinicke et al. [Steinicke et al. 2010], a straight path in the VE can be turned into a circular arc in the real world with a radius of at least 22m, for which users are not able to consciously detect manipulations. Furthermore, rotations can be scaled with gains between 0.67 and 1.24 and translations with gains between 0.86 and 1.26, for which users are not able to consciously detect manipulations. These results have been reproduced and extended in several experiments, e.g., [Bruder et al. 2012; Grechkin et al. 2016; Langbehn et al. 2017; Matsumoto et al. 2016; Neth et al. 2012]. For example, Grechkin et al. found that a radius of only 12m can be sufficient for unlimited straight walking in a VE [Grechkin et al. 2016]. The differences in the results between those experiments could be explained by the different hardware that was used in the experiments as well as methodological and population differences. In general, current hardware appears to improve RDW techniques.

Using electrical stimulations for RDW is a promising approach. For example, galvanic vestibular stimulation is a technology that uses electrical stimulation via electrodes placed on the mastoid bones behind each ear to stimulate the vestibular system. Sra et al. implemented a VR game based on galvanic vestibular stimulation for redirection of the players [Sra et al. 2017].

2.2 Transcranial Direct-Current Stimulation

tDCS is a non-invasive stimulation technique and its application to the respective cortical area has been shown to modulate spontaneous brain excitability and activity, for example, anodal stimulation typically increases whereas cathodal stimulation decreases excitability [Nitsche and Paulus 2000]. Several studies have established that tDCS can affect not only the stimulated region but also functional network [Antal et al. 2012; Keeser et al. 2011; Weber
et al. 2014]. The use of tDCS together with VR has been receiving increased attention, primarily due to its potential therapeutic use in neurological disorders [Massetti et al. 2017]. However, the effect of tDCS on RDW is scarcely known. Previous studies have shown that a widespread parietal-prefrontocortical network underlies spatial navigation, whereby the prefrontal cortex is particularly relevant for information processing relative to the target of navigation [Blankenship et al. 2016; Byrne et al. 2007; Epstein 2008; Ito et al. 2015; Spiers 2008; Spiers and Maguire 2006]. More specifically, spatial navigation can involve, to different extents, egocentric and allocentric reference system components as well as higher cognitive limbic and cortical processes [Byrne et al. 2007; Taube et al. 2013]. Thus, there is a wide range of brain regions, of which stimulation may affect redirected walking. While a proper exploration of all regions is beyond the scope of this investigation, here we placed the cathode over the right prefrontal cortex (AF4) and the anode over the parietal cortex (Pz). Stimulation at these regions has been shown to affect spatial navigation, and modulate effective connectivity during spatial navigation [Hampstead et al. 2014]. Cathodal stimulation over the occipital region was not targeted here as this region is relevant for the processing of large field motion, a function definitely required for movement within the VE [Dupont et al. 1997].

3 EXPERIMENT

In this experiment, we evaluated the effect of tDCS on RDW as well as on other important parameters like cyber sickness and presence. In particular, we analyzed boding gains for this experiment as presented by Langbehn et al. [Langbehn et al. 2017].

Due to the interdisciplinary nature of our approach combining neurostimulation and VR, the experiment was approved by two ethics commissions: The ethics commission of Universität zu Lübeck, which evaluated the use of tDCS, and the ethics commission of Department of Informatics at Universität Hamburg, which evaluated the use of immersive technology.

3.1 Participants

Eligible for participation in the experiment were non-smoking and healthy subjects between 18 and 40 years who were free of medication (except oral contraceptives). Females were only permitted to participate if they took oral contraceptives since it is reported that hormonal fluctuation could impact the effect of tDCS [de Tommaso et al. 2014]. Furthermore, pregnant women, subjects with a pacemaker, any history of epileptic seizures, childhood absence epilepsy or migraine, and people with brain injuries or any known disorder of the central nervous or cardiovascular system were not permitted to take part in the experiment. Participants were instructed not to take caffeine, alcohol, drugs, or medicine (except oral contraceptives) on the days of the experiment. By excluding all of these things, we wanted to make sure that there are no external influences on tDCS.

The experiment was completed by 34 subjects (3 female and 31 male, ages 19–36 years, M = 24). One participant of the initial 35 had dropped out due to non-experiment related sickness. For the analysis, we had to exclude four additional participants due to sickness or because they took medicine. Thus 30 participants entered the analyses. This number of participants is sufficient for our estimated effect size of $d = .8$ ($p = .05$). The participants were students, who obtained class credits, or professionals at the local Department of Informatics. The body height of the participants varied between 1.68–1.97 m ($M = 1.82$ m, $SD = 0.07$ m).

All of our participants had normal or corrected-to-normal vision. Ten participants wore glasses during the experiment and one wore contact lenses. None of our participants reported having any disorder of equilibrium. One participant reported having a dyschromatopsia, one a strong eye dominance, one a deuteranomaly, and one an ambylophia. None of these disorders were considered sufficient to exclude any subject from the analysis. No other vision disorders were reported by our participants. To determine the eye dominance, the thumb test was conducted. Participants had to extend one arm out and holding the thumb of that hand in an upright position while keeping both eyes open and focused on a distant object. Then, they superimposed their thumb on that object and alternately closed one eye at a time. According to this test, 18 participants had a right eye dominance and 12 had a left eye dominance. All participants were right handed.

All participants had used HMDs before. Their average experience with HMDs was $M = 3.25$ ($SD = 1.06$, in a range of $1$ = no experience to $5$ = much experience). The experience of the participants with 3D stereoscopic displays (cinema, games etc.) in a range of $1$ (no experience) to $5$ (much experience) was $M = 3.15$ ($SD = 1.18$). Most of them had some experience with 3D computer games ($M = 3.71$, $SD = 1.60$, in a range of $1$ = no experience to $5$ = much experience) and they usually played 8.31 hours per week on average ($SD = 6.88$).

3.2 Materials

The experiment took place in a 5m × 7m laboratory room. We instructed the participants to wear an HTC Vive HMD (see Figure 1a), which provides a resolution of 1080 × 1200 pixels per eye with an approximately 110° diagonal field of view and a refresh rate of 90 Hz. Positional tracking was done by a Lighthouse tracking system that is delivered with the HTC Vive. The Lighthouse system was calibrated so that there was an available walking space of 4m × 4m. The participants received instructions on slides presented on the HMD. An HTC Vive controller served as an input device via which the participants provided responses during the experiment. The participants wore a backpack during the experiment which contained the tDCS stimulator. For rendering, system control, and logging we used an Intel computer with 3.5 GHz Core i7 processor, 32 GB of main memory and two Nvidia GeForce GTX 980 graphics cards. The VE was rendered using the Unity3D engine 2017.1 and showed a curved path in front of the participant (see Figure 2). The path was computed by first calculating a circle with a radius of 3m and then drawing only that part of the circle that started at the virtual camera position and ended after 4m. Dependent on the current condition, the path was curved to the right or to the left. Hence, the center point of the circle was to the left or to the right of the virtual camera position.

TDCS was delivered using a commercial stimulator (Edith DC Stimulator, Neuroconn GmbH, Ilmenau, Germany) via a pair of square rubber electrodes (3 × 3 cm; see Figure 1b). The cathode electrode was placed over AF4 while the anode was placed over
Figure 1: The experimental setup: a user is wearing the HTC Vive HMD, a hand controller for input, two electrodes at the head, and a backpack for the tDCS stimulator (a). The tDCS stimulator and the electrodes in detail (b).

Pz (according to the international 10-20 system for EEG electrode placement). Our decision for these electrode positions is based on the research presented in section 2.2 that found that the prefrontal cortex is particularly relevant for information processing relative to the target of navigation. Following disinfection the stimulation sites were prepared using an abrasive gel. Thereafter a conductive adhesive paste (EC2, Natus, Middleton, USA) was spread evenly across the electrodes. A current strength of 1.25 mA was applied. Further details are given in section 3.3.1.

3.3 Methods

We used a $5 \times 8 \times 2$ full-factorial within-subjects experimental design. We tested 5 different gains $g_B \in \{\frac{3}{1.57}, \frac{3}{2.27}, \frac{3}{2.94}, \frac{3}{3.61}, \frac{3}{4.28}\}$ (the real radius varied while the virtual radius always stayed 3m) which correspond to actual rotations of $3^\circ$/m, $6^\circ$/m, $9^\circ$/m, $12^\circ$/m, and $15^\circ$/m. Each gain was repeated 8 times: 4 times with a left curve and 4 times with a right curve. Participants had to complete 2 sessions: one session with tDCS and one without (Sham). In total, the participants completed $5 \times 8 = 40$ trials per session. All trials in one session were randomized.

These gains were chosen based on previous work as described in Rietzler et al. who reported detection thresholds around $5.5^\circ$/m for bending gains and recommended to use gains that scale in a linear way with the perceived manipulation [Rietzler et al. 2018].

3.3.1 Procedure. The two sessions were carried out on different days separated by at least one week. On both days subjects participated at the identical time of day. The procedure of both sessions was the same so that participants were blinded as to which session stimulation was conducted. The order of conditions was counterbalanced across subjects, i.e., half of the participants started with the tDCS condition, the other half with sham.

Before the experiment, all participants filled out informed consent forms and received detailed instructions about the experiment and on how to perform the experimental task. Furthermore, they filled out a questionnaire about their experiences with VR, stereoscopic displays, and games, a handedness questionnaire, a questionnaire about vision impairments, and a general questionnaire about diseases, medication, and sleeping habits.

Before each session, participants filled out the Simulator Sickness Questionnaire (SSQ) [Kennedy et al. 1993]. Subsequently, in the tDCS as well as sham condition electrodes were applied using the gel and paste.

Participants completed four training trials before the actual experimental trials. After the training trials and the subject had returned to the start position, the stimulation was turned on for 1200s (20 minutes) in the tDCS condition, which included a 30 seconds ramp up and down period at the beginning and end of the stimulation, respectively. In the sham condition, currents were only
ramped up and down for 30 seconds at the beginning of the session. After these 30 seconds no stimulation was applied.

For each trial, participants were instructed to walk along the virtual path shown in the VE. When they reached the end of the path, they had to press a button on the controller, turn around, and walk back to the beginning of the path. In one of these walking directions a bending gain was applied as explained in Section 3.3. After the participants reached the beginning of the path again, they pressed a button on the controller and had to answer the displayed question using the touchpad of the controller (see Section 3.3.2). Afterwards, participants were guided to the next start position in the laboratory by displaying a 2D compass and distance metrics in the HMD. By using this method, the participants were kept unaware of their position and orientation in the real world. This, they could not use this information to identify the amount of redirection that was applied. The next trial started once participants reached the new initial position and indicated that they were ready to start by pressing a button on the controller.

After the session, participants filled out the SSQ again, the Slater-Usoh-Steed (SUS) presence questionnaire [Usoh et al. 1999b], and a demographic questionnaire, and the electrodes were removed. The total time per participant for each session, including pre-questionnaires, application of tDCS electrodes, instructions, experiment, breaks, post-questionnaires, and debriefing, was about 120-150 minutes, out of which around 25 minutes were spent in VR.

3.3.2 Two-Alternative Forced-Choice Task. To measure the amount of deviation that is unnoticeable, we used a standard psychophysical procedure based on the Two-Alternative Forced-Choice (2AFC) task. This experimental method is a common procedure in RDW research [Steinicke et al. 2010].

The participants have to choose between one of two answer possibilities, usually if they walked “left” or “right” of the virtually visible path. At least, this works for curvature gains [Steinicke et al. 2010]. In our case, using bending gains, previous experiments showed that participants had serious problems in identifying on which side of the virtual path they physically walked. For instance, participants mentioned that they noticed a redirection in terms of “something strange happened” but could not detect reliably at which side of the path they walked [Langbehn et al. 2017]. This is because participants adapted to the redirection and walked on the virtual path, which made it hard for them to estimate on which side of the path they are located in the real world. Another method was introduced to the RDW community, which seems to produce more stable results for bending gains [Rietzler et al. 2018].

According to this method, participants walk two times the same path while only one of the paths is manipulated. Then, the following question is displayed: “Which path was manipulated?” They have two answer options “First (There)” or “Second (Back)”. Answers like “I don’t know” are not allowed. Instead, the participants have to choose one option randomly and will be correct in 50% of the cases on average. The bending gain at which the participants detected the manipulated path correctly in 50% of the trials is taken as the point of subjective equality (PSE), at which the participants estimate the curvatures in the virtual and in the real world as identical. As the gain increases from this value the ability of the subject to detect the difference between physical and virtual movement increases, resulting in a psychometric curve for the discrimination performance. When the participant’s answers converge to 100% chance level, it is more likely that they can detect the redirection reliably. A threshold is the point of intensity at which participants can just detect a discrepancy between physical and virtual motion. However, stimuli at values close to thresholds will often be detectable. Therefore, thresholds are considered to be the gains at which the manipulation is detected only some proportion of the

Figure 2: Illustration of the virtual environment shown to the participant. The curved path was part of a circle with the radius of 3m and had a length of 4m.

Figure 3: The pooled results of the 2AFC task over all participants. The x-axis shows the applied gain in degrees per meter. The y-axis shows the probability of correctly detecting the manipulated path. Results of the sham condition are plotted in black and results of the tDCS condition are plotted in red. For each gain, the mean and standard error bars are displayed.
time. In psychophysical experiments, usually the point at which the curve reaches the middle between the chance level and 100% is taken as a threshold. Therefore, we define the detection threshold (DT) for gains greater than the PSE to be the gain at which the subject chooses the manipulated path correctly in 75% of the trials.

3.4 Results
In this section, we describe the results for the 2AFC task, subjective estimates of cyber sickness and presence, and the additional questionnaires responses.

Where appropriate, we analyzed the results with a t-test at the 5% significance level. In cases in which a Shapiro-Wilk test revealed that the data is not normally distributed, we analyzed the results with a Wilcoxon test at the 5% significance level.

3.4.1 Detection Thresholds. (DT)
Figure 3 shows the pooled results of the 2AFC task over all participants. The x-axis shows the applied gain in degrees per meter. The y-axis shows the probability of correctly detecting the manipulated path. Results of the sham condition are plotted in black and results of the tDCS condition are plotted in red. For each gain, the mean and standard error bars are displayed. Each curve was fitted with a sigmoidal psychometric function which determines the DT. In the tDCS condition, the DT is at 7.3143°/m. In the sham condition, the DT is at 7.413°/m.

Additionally to these pooled results over all participants, we calculated individual plots and DTs for each participant (see table 1). These DTs were used to perform a significance test in order to compare the thresholds between sham and tDCS condition. We did not find any significant differences (p = .514).

Furthermore, we compared the mean probability for each gain between sham and tDCS condition. We did not find any significant differences for the 3°/m gain (p = .927), the 6°/m gain (p = .848), the 9°/m gain (p = .812), or for the 12°/m gain (p = .608). We found a significant difference for the 15°/m gain (p = .018), indicating that the mean probability of correctly detecting the manipulated path was higher in the tDCS condition.

3.4.2 Cyber Sickness.
In the sham condition, we measured a mean SSQ-score of 11.47 (SD = 11.98) before the experiment, and a mean SSQ-score of 17.83 (SD = 18.5) after the experiment. In the tDCS condition, we measured a mean SSQ-score of 19.2 (SD = 12.98) before the experiment, and a mean SSQ-score of 17.7 (SD = 19.44) after the experiment.

We did not find any significant differences between total SSQ-scores before and after the experiment for the sham condition (p = .162) and the tDCS condition (p = .291). However, we also calculated the scores for the three subsections of the SSQ: oculomotor, nausea, and disorientation. Results are shown in Figure 4 (a) and (b). We observed a significant increase of disorientation in the sham condition (p = .008) but not in the tDCS condition (p = .308). We found a significant decrease of oculomotor sickness symptoms in the tDCS condition (p = .016) but not in the sham condition (p = 1.0). We did not find any significant differences for nausea in the sham (p = .142) or tDCS conditions (p = .06).

3.4.3 Presence. The mean SUS-score for the sense of feeling present in the VE was 2.16 (SD = 1.84) on a five-point Likert scale in the sham condition and 2.26 (SD = 1.6) in the tDCS condition. We did not find any significant differences of SUS-scores between sham and tDCS conditions (p = .729).

3.4.4 Additional Questionnaires. When the participants were asked "Did you feel a stimulation during this session?" at the end of each session, two participants answered yes after sham condition and three participants after the tDCS condition. Other than on these few sessions, subjects did not report on having felt the stimulation.

When the participants were asked "Do you think that this session was the session with stimulation or without?" after the sham condition, 14 participants said "Sham" and 6 "Stimulation" (the rest did not know). After the tDCS condition, 9 participants said "Sham" and 8 "Stimulation."

On average participants spent 24.3 minutes (SD = 4.4) for all experiment trials. In the tDCS condition, it was 23.7 minutes (SD = 4.3), and, in the sham condition, it was 24.9 minutes (SD = 4.5).

We did not find any significant difference between the duration of sham and tDCS conditions (p = .295).

4 DISCUSSION
The working hypothesis of the present experiment was that cathodal tDCS over the prefrontal cortex would have a significant effect on RDW performance. Based on our power analysis, we designed the experiment and 2AFC task accordingly. Unfortunately, this hypothesis was not supported by our results: Overall, the detection thresholds for the sham and tDCS conditions did not reveal any significant differences. As discussed below one reason may be that our tDCS protocol did not sufficiently target the involved brain regions. Although, it cannot be excluded that tDCS is inadequate to affect RDW performance, it would be premature at this stage to draw such a conclusion.

In fact, we did find an effect of tDCS for the highest redirection gain, i.e. when redirection was the strongest. This effect indicates it was easier for the participants to detect the redirection in the tDCS condition. Thus the effect was opposite to that of our working hypotheses. There are at least two conclusions to be drawn from the experimental results. Firstly, the distribution of cortical activity specifically involved in our RDW task, which involved in conflicted proprioceptive, vestibular and visual sensation [Bruder et al. 2015], is scarcely known. Thus, although we intended to suppress excitability in the prefrontocortical network relative to the parietal network, and thereby subdue perceived deviation between real and virtual pathways, this may have not been the optimal strategy. Based on our results, a better strategy may have been to relatively suppress the parietal network, as the direction of effects was contrary to our hypotheses. Interestingly, since a facilitated detection of deviance between virtual and real paths occurred with an anodal return current over Pz, and anodal tDCS is typically associated with enhancing excitability, our findings might carefully be taken to suggest a relevance of parietal networks in detecting RDW. Nonetheless, further investigations along these lines are needed.

Egocentric navigation has been associated with egocentric representations in the parietal cortex (precuneus and cuneus, inferior parietal lobe [Colombo et al. 2017; Nemmi et al. 2017]), yet these structures lie deeper than the presumed primary cortical target
area of stimulation. Thus a direct effect of Pz stimulation cannot be simply concluded.

Secondly, the finding that tDCS was efficient only when redirection was strongest suggests that efficacy of tDCS requires a comparatively high cognitive, in which a high cognitive load has been shown for such high redirection gains [Bruder et al. 2015]. It could be speculated that only conditions of high cognitive load would enable endogenous cortical activity to emerge to a sufficient level as to be modified by the subtle effects of tDCS. A higher current density was not used in the present study in order to blind subjects as to the tDCS and sham sessions, which employed only two stimulation sites. This problem may in the future be circumvented by the use of multiple stimulation electrodes. Further experiments will reveal whether stimulation of the opposite polarity may thus indeed suppress detection of path deviation.

Furthermore, we found very interesting results for the influence of tDCS on features of cyber sickness. Oculomotor sickness symptoms, which includes fatigue, headache, eye strain, and difficulty concentrating, decreased during the tDCS session as compared to baseline. In contrast, disorientation, which includes symptoms like fullness of head, blurred vision, vertigo, and dizzy, increased during the sham, but not during the tDCS session. These findings show that our tDCS protocol counteracted cyber sickness symptoms in VR, and support results of another study, in which anodal tDCS applied at the temporoparietal junction ameliorated subjective disorientation symptoms possibly by affecting the visual-vestibular system function [Takeuchi et al. 2018].

To our best knowledge, these are the first results indicating potential effects of tDCS on locomotion and interaction in VR, which we believe are highly interesting for this field to be studied in more detail in future work.

5 CONCLUSION

In this paper, we presented a study in humans investigating the use of tDCS to change the sensitivity to RDW manipulations. Although, our results do not show a strong effect of tDCS on detection thresholds for low and medium redirection gains, the experiment revealed an interesting effect for strong gains, which might suggest an interaction between tDCS and cognitive load in VR. Moreover, our results showed interesting insights into the general use of tDCS in VR. For instance, it might be possible to reduce cyber sickness symptoms during VR exposure with tDCS.

While this paper presents the first results on the use of tDCS in the scope of locomotion and interaction in VR, we see much potential in extending this line of research in future work. In particular, we seek to repeat the experiment under a wider range of tDCS stimulation with different regions of the brain. Therefore, we plan to record EEG during RDW in VR to identify brain regions that are especially involved and should be targeted with tDCS. Furthermore, we will extend our experiments to other VR interaction tasks beyond RDW.

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Table 1: Individual detection thresholds for each participant in the sham and tDCS conditions in °/m. No significant differences between sham and tDCS were found.

<table>
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