# Omnidirectional Galvanic Vestibular Stimulation in Virtual Reality

Colin Groth, Jan-Philipp Tauscher, Nikkel Heesen, Max Hattenbach, Susana Castillo, and Marcus Magnor, *Member, IEEE*

Fig. 1. To reduce cybersickness for moving-camera sequences in VR, we evaluate the effectiveness of galvanic vestibular stimulation. We stimulate the VR user's vestibular sense in all three spatial directions taking the motion of the camera in the 360° video as well as the user's current viewing direction into account. This way, we aim to reconcile visually induced and felt self-motion.

**Abstract**—In this paper we propose omnidirectional galvanic vestibular stimulation (GVS) to mitigate cybersickness in virtual reality applications. One of the most accepted theories indicates that Cybersickness is caused by the visually induced impression of ego motion while physically remaining at rest. As a result of this sensory mismatch, people associate negative symptoms with VR and sometimes avoid the technology altogether. To reconcile the two contradicting sensory perceptions, we investigate GVS to stimulate the vestibular canals behind our ears with low-current electrical signals that are specifically attuned to the visually displayed camera motion. We describe how to calibrate and generate the appropriate GVS signals in real-time for pre-recorded omnidirectional videos exhibiting ego-motion in all three spatial directions. For validation, we conduct an experiment presenting real-world 360° videos shot from a moving first-person perspective in a VR head-mounted display. Our findings indicate that GVS is able to significantly reduce discomfort for cybersickness-susceptible VR users, creating a deeper and more enjoyable immersive experience for many people.

**Index Terms**—Galvanic Vestibular Stimulation, GVS, Virtual Reality, VR, 360 Videos, Cybersickness, Presence.

## 1 Introduction

While virtual reality (VR) is not a new technology, it is only in recent years that it has started to win more and more support and acceptance in society [44]. This trend is driven by new VR devices as well as an increasing number of games, videos and even movies for VR. However, this encouraging progress also raises the bar for expectations and the acceptance of the general public.

A main reason that curbs the spread of immersive content are feelings of discomfort caused by the VR experience. The most commonly known adverse effect is cybersickness (CS). This term describes any physical discomfort evoked by visually perceived motion that is not actually experienced [25, 32]. The mismatch between the visual and vestibular channel is the origin of CS as described by the *sensory conflict theory* [42], one of the most accepted theories. CS covers an extensive collection of symptoms which include, in a low state, oculomotor effects (e.g., blurry vision), headaches, and dry eyes. In severe cases, the user can even experience disorientation and nausea [26, 52]. Although CS is widely known for VR games and virtual worlds, it is not explored much and sometimes underestimated for real-world content in VR. Still, CS can have huge consequences and strong implications for immersive video material [15, 22, 28].

For scenes were ego-motion is visually perceived, a common way to reduce CS is to minimize the optical flow, e.g., with a reduced field of view (FOV) or blurred outer regions [1, 4, 21, 22]. These techniques reduce the visual motion and readjust it to the vestibular sensation. Thereby, the compensation of rotational movements is particularly important as they contribute most to CS [22, 29]. While these methods are effective against CS, the observer's perception is moved away from the virtual experience back to the sensations of the real world. As a result, the feeling of presence of the viewers can suffer. For VR scenes it is most important to create experiences that feel as real as possible and, thus, evoke high presence. Accordingly, we require the vestibular system to perceive the same movements like those visually observed from the VR scene. Using galvanic vestibular stimulation (GVS), the vestibular system can be influenced with small currents inducing a feeling of motion that is different from the real-world sensation. As the currents are kept very small (typically below 2.5mA) this process is safe and has no lasting effects [56].

Former research on galvanic vestibular stimulation (GVS) in the field of computer graphics typically employs systems with two electrodes and consequentially only one axis that can be stimulated. This bilinear model is sufficient as long as the stimulation of only one axis is necessary, e.g. for simple racing games. However, as soon as the axis changes, e.g. by turning the viewer's head, a more complex stimulation model is needed. Especially the complex, unpredictable trajectories of real-world 360° videos would need a precise stimulation to truly adapt the vestibular system to the perceived virtual movements. Surrounding

- *C. Groth, J-P Tauscher, N. Heesen, S. Castillo, and M. Magnor are with the Institute for Computer Graphics at TU Braunschweig, Germany. E-mail: {groth, tauscher, heesen, castillo, magnor}@cg.cs.tu-bs.de.*
- *M. Hattenbach is with Universität Osnabrück. E-mail: mhattenbach@uni-osnabrueck.de.*

*Manuscript received September 2021; accepted January 2022. Date of Publication February 2022; date of current version March 2022. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: 10.1109/TVCG.2022.3150506*

video material can provide sophisticated viewing experiences in VR. Such experiences allow the spectator to deeply immerse in the content and see the world through the eyes of the narrator. While the linear story unfolds around them, viewers can turn their heads in arbitrary directions. Similar to traditional linear video formats like TV shows or movies, the recording takes place from the position of the camera but the viewers are in control of their own gaze. Unfortunately, it is not yet possible to precisely stimulate the multidimensional movements that are presented in such experiences.

In this work we introduce omnidirectional GVS to VR. This paper is particularly focused on immersive videos and VR applications without body movements of the user. However, for simplification, the term VR will be used throughout the paper. In an experiment, we show the capability of 3-dimensional GVS to effectively mitigate CS while increasing the user experience. The applied GVS is implemented via an oculo-vestibular recoupling (OVR) stimulation model with two variations and compared to a control condition (CC). With the first variation, we followed related work and stimulate only the strongest visual main rotation axis per frame. For the second variation, we stimulate the exact rotation axes as experienced by the viewer by interpolating the electrical currents. Our GVS is dynamically computed during runtime and considers the user's head position in real-time additionally to the scene rotation. We performed an experiment with real-world moving-camera 360° videos with depth information. For the experiment we developed our own custom-built video player that allows for fast and high-resolution video playback.

The contributions of the paper are as follows:
(1) Implementation of 3D GVS for VR by OVR stimulation.
(2) First time interpolation of electrical currents and evaluation of the effects.
(3) Comprehensive experiment to investigate the effectiveness of 3D GVS on CS and discomfort mitigation for immersive videos.

## 2 Related Work

### 2.1 Visual Mitigation Techniques for Cybersickness

Given the ubiquity of CS, a lot of works study the mitigation of CS in user-controllable virtual environments like games that usually give the user 6 degrees of freedom (DOF) to explore the scene.

General concepts to reduce CS in VR scenes cover high frame-rate renderings, high quality tracking and reduced latency systems [11, 31, 45].

Recently, the use of techniques that manipulate the visual stimulus before it is presented to the VR user has increased. These techniques focus on the reduction of optical flow in the peripheral viewing area. Typically, either a complete masking of the outer viewing areas is achieved [1, 16, 21, 33] or the peripheral viewing area is covered semi-transparently [6, 21, 34]. On the downside these methods often lead to adverse effect on the feeling of presence in the scene.

One important but least explored field in VR includes 360° videos and VR movies. This field of immersive presentation comprises a wide range from personal holiday videos to car configurators and blockbusters. Due to the sophisticated form of immersive presentations to view a scene, users are able to perceive real-world content more intense and realistic as with classic displays. Yet, as with other VR content, 360° videos provoke CS when movements are shown in the VR glasses that are not perceived by the user [15, 28]. The multimodal perception of stimuli, such as haptics, to enhance virtual experiences was also shown by Danieau *et al.* [9]. Elwardy et al. evaluated CS for 360° videos in VR [15]. The authors were particularly interested in how the level of VR experience influences the outcome. As a result mainly participants with low experience in immersive media suffered from CS.

The high risk of CS for viewers exposed to 360° videos was also recognized by Kim et al. [28]. Their solution was a neural network that predicts a sickness score for VR videos. Consequentially, their idea is to warn about videos that are most likely to make users sick rather than mitigate CS in these videos.

Bala et al. [3] started investigations on CS mitigation for real-world 360° videos. They used an independent background grid, a fixed FOV reduction and a combination to reduce CS in an experiment. According to their own statement, their results did not show any significant difference in CS due to the small number of participants [3]. In a later work with 360° videos they included more participants and only focused on the combined method (independent background grid and reduced FOV) and were able to show a decrease of CS [4].

Recently, Groth *et al.* [22] demonstrated that CS in 360° videos is mitigated by unobtrusive modulations of the visual presentation. Their idea was to reduce motion in the peripheral area and thus minimize the sensory conflict. In their experiment they gaze-contigently modified the peripheral visual field by either blurring or opaque occluding eccentric view areas. The experimental results show that both techniques are effective to mitigate CS in pre-recorded VR content with the opaque occlusion delivering the best results.

For immersive videos, minimizing the conflict between visual and vestibular sensations is crucial to prevent CS and increase the overall well-being [9, 42]. Particularly interesting are the efforts that adapt the vestibular stimulus without removing any information from the visuals.

The work of McGill *et al.* [36] highlights how the adjustment of vestibular stimuli affects CS and immersion. In an in-car experiment the movements of a 360° video were synchronised with the real vehicle movements. Unfortunately, no best practice for driving simulator-based presentations were found. Still, as one result people got more sick in a moving car with VR applied, which underlines the sensory conflict theory.

The video format (monoscopic, stereoscopic) and audio format (stereo, spatialized) was found to not influence the users' feeling of presence and CS for 360° videos [40]. In contrast, gender is a significant variable that should be considered for VR scenes that display 360° videos [40].

### 2.2 Electric Stimulation

GVS is the direct and safe stimulation of the vestibular system by electrical currents [56]. It is a subset of transcranial direct current stimulation (tDCS), a method often used in medicine, e.g. for therapy or tumor treatment [5, 41, 48]. While tDCS is applied by electrodes attached to the subject's scalp, the electrodes for GVS are usually attached to the mastoids behind the ears to specifically stimulate the vestibular canals. When standard procedures are followed, tDCS and GVS are safe, noninvasive and low-cost techniques that have been extensively studied and applied in practice [56].

The most commonly used form of GVS is bilateral, bipolar stimulation where two electrodes are placed on the mastoids. With this GVS, the sensation of a strong roll rotation and a weak yaw rotation towards the cathode is elicited [10, 17].

The name *galvanic stimulation* is based on the research of Luigi Galvani from 1791 who conducted early experiments on animal electricity [19]. Around the same time, Alessandro Volta, a rival and critic of Galvani's work, performed the first human GVS experiments on himself. He felt his head spinning and reported to hear a noise, which is probably based on the high voltage he used. Today's applications of GVS use only very weak currents of no more than 2.5 mA. These applications of GVS are often found in medical research and treatment. Positive effects of electric stimulations have previously been reported for motor, visual, somatosensory, attentional, vestibular and cognitive functions as well as multiple neurological and psychiatric disorders [56].

However, medicine is not the only field where GVS has been applied. In the work of Byrne *et al.* [7], GVS is explored as a design tool for vertigo games. In their application *Balance Ninja* two players try to unbalance each other by controlling a GVS device connected to the other person. Based on the positive response of the participants, the results suggest considerable potential of GVS as a game design tool.

The insights of further research support the hypothesis that GVS can be a successful tool not only in medicine, but also for entertainment and VR.

Already in 2005, Maeda *et al.* [35] revealed that visually induced vection, i.e., the illusion of self-motion, can be enhanced with GVS. In their experiment participants were stimulated with GVS while watching white dots move on a screen. Thereby, the intensity of the movements and the GVS were matched. As a result participants reported a strong feeling of vection by GVS as long as the sensory conflict was low.

Aoyama *et al.* [2] investigated the enhancement effect of GVS with counter-currents on human acceleration perception. In their experiment they used a 4-pole GVS with a capacitor-resistors circuit model in VR. They found that counter-current stimulation enhances the strength of the acceleration sensation whereby the duration of the stimulation correlates with the perceived strength.

### 2.3 GVS for Cybersickness Reduction

In 2007, GVS was applied to counter CS in VR for the first time [43]. In multiple sessions the visual and vestibular stimulus was either turned on or off while participants performed a driving simulation. In these early VR experiments the GVS was activated by hand by the researchers. In conclusion, the results already gave a positive outlook for CS reduction when GVS is applied.

Over the years several manuscripts using bilateral GVS were published but mostly do not address cybersickness [18, 35, 37, 51].

One of the most extensive experiments with a bilateral GVS was presented in 2019 by Sra *et al.* [50]. They constructed a 2-electrode GVS device that is hung around the neck. With the device and a mobile phone companion app, the vestibular feedback can be predefined on one stimulation axis for a given scene. The results of their experiment show significantly lower levels of CS while the immersion is higher when the GVS is applied.

Typically, the stimulation of the vestibular system is done with electrical currents. Also, bone-conducted vibration can be used as a stimulus as shown by Weech *et al.* [58] who reduced CS with this GVS alternative. In an experiment with a VR head-mounted display (HMD) and a projection cave, they got positive results for sickness reduction. The vibrations achieved the same effect when they were randomly induced in comparison with time-coupled stimulations to angular accelerations. Still, this technique remains uncommon in VR research and has a lower impact as electrical stimulation [59].

Later, the same researchers moved their focus to noisy GVS as a promising technique to stimulate the vestibular system when the visual movements in the scene are unknown. In a VR experiment they focused on sickness severity during and immediately following noisy GVS. They state that noisy stimulation is able to reduce CS severity for intense VR content, while it has no effect for moderate content. Even more interesting for GVS research is the result that a rapid re-adoption of the vestibular system to its normal state happened after GVS exposure. As no effect persisted after the experiment, this is a positive outlook for the overall safety of GVS.

In the work of Cevette *et al.* [8], the oculo-vestibular recoupling (OVR) stimulation model is presented. By using a 5-electrode GVS device they were able to stimulate the three main rotation axes (yaw, pitch, roll) individually. In their experiment the visual stimuli were presented on a screen in front of the participants who controlled a flight simulator with a joystick. In their approach they synchronized the rotational speed and main direction of the visual movements with the GVS induced vestibular sensation of the participants. Their results show that OVR based stimulation significantly reduces simulator sickness (SS) in a cockpit flight simulator.

In our work, we build upon the work of Cevette *et al.* and use OVR-based GVS to re-adjust the vestibular perception of VR users to their visual impression. With a 5-electrode GVS device we apply two different methods. First, we stimulate only the strongest visual rotation axis comparable to former work. Second, we stimulate the exact visually perceived movements by interpolating GVS currents between electrodes.

## 3 Methods

In a VR experience, we elicit a feeling of self-motion that corresponds to the visual movements of the virtual scene. The movements are visually induced by a 360° video and vestibularly stimulated with a GVS device. In the following we describe the implementation necessary to achieve this particular experience.

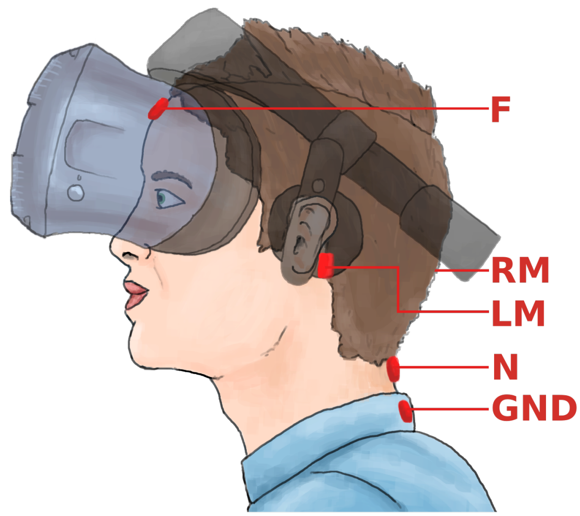


Fig. 2. Placement and naming of the five electrodes (red) for the GVS. RM is placed on the right mastoid similar to LM.

### 3.1 GVS

For the GVS we apply the OVR stimulation model proposed by Cevette *et al.* [8]. With the five electrode OVR model all single Euler rotations (yaw, pitch, roll) can be stimulated by one negative and one positive pole on defined electrode positions [8].

As proposed, we attach two electrodes to the left and right mastoid (LM and RM), one electrode to the forehead (F), one electrode to the neck (N) below the hair line, and one ground electrode further down the neck (GND). Yaw is stimulated with the two electrodes on the mastoids. Pitch and roll on the other hand are defined by two different electrode pairs (see Table 1). The coordinate system of the camera is left-handed and the Euler angles are defined in the order: yaw, pitch, and roll. All recorded rotations are given in world coordinates and are further transformed with the transformation of the VR headset (see details below).

In theory, any intermediate axis is represented by a linear combination of the principle components of the Euler rotations. To interpolate main rotations with OVR, the relevant electrode pairs have to be carefully chosen to prevent negative influences on the current flows. Accordingly, one electrode should not be considered as a negative pole for the stimulation of one rotation axis while at the same time it serves as a positive pole for another rotation. To date, such a linear combination of the rotation axes does not exist in the literature. Therefore, we conducted an internal study among the authors to empirically verify the validity of a interpolated stimulation. In the internal study we tested all possible combinations of the single main rotation axes with OVR stimulation. Note that the combinations especially consider all potential electrode pairs to stimulate one particular axis (cf. Table 1). In this pre-experiment the participants were standing with their eyes shut and did not know what stimulation they were receiving. We evaluated the

Table 1. Directional stimulation used by OVR to cause a particular motion perception [8]. The electrode naming follows Fig. 2. Annotation for current stimulation: anode to cathode.

| Intended Motion | Current Flow Direction |
|---|---|
| yaw right | LM to RM |
| yaw left | RM to LM |
| pitch forward | RM to F \|\| LM to F |
| pitch backward | F to RM \|\| F to LM |
| roll right | N to LM \|\| RM to N |
| roll left | LM to N \|\| N to RM |

combinations through body tilt and perceived stimulation direction via oral feedback. Our results show that a linear combination of the single rotation axes is capable of representing all intermediate angles when the electrode pairs for pitch and roll are chosen correctly. Following our theory, the intermediate angles are stimulated by combined currents of the respective Euler angle components (yaw, pitch, roll).

This interpolated currents per electrode are defined by function $f$ (see Equ. 1–4). Here, the name of the electrodes follows the previous convention.

$$f_F = \beta \tag{1}$$
$$f_{LM} = k + H(\gamma)sgn(k)\gamma \tag{2}$$
$$f_{RM} = l + H(-\gamma)sgn(l)\gamma \tag{3}$$
$$f_N = -H(\gamma)sgn(k)\gamma - H(-\gamma)sgn(l)\gamma \tag{4}$$

As input, all functions take the three components of the Euler rotation defined by $\alpha$ for yaw, $\beta$ for pitch and $\gamma$ for roll.

The variables $k$ and $l$ are given by:

$$k = \alpha - H(-\beta) * \beta$$
$$l = -\alpha - H(\beta) * \beta$$

The Heaviside step function $H(x)$ is defined as usual. The sign function $sgn(x)$ is defined by:

$$sgn(x) = \begin{cases} 1, & x > 0 \\ -1, & x \leq 0 \end{cases}$$

For the stimulation of the intermediate angles we consider every axis by its weight and in a clear order. We assign a maximum current per user to consider individual tolerances. This maximum current value per electrode per participant is determined during the calibration phase (described in more detail in Sec. 4.5). In the experiment we take care that the currents never exceed this value. Also, the stimulation per frame depends on the angular velocity per axis in relation to the pre-defined maximum speed of the video.

In the experiment, we only stimulate the movements that are actually seen by the VR users in their FOV. To achieve this dynamic stimulation, we consider the pre-recorded movement of the recording device and the real-time head transformation of the VR glasses. The camera rotations were recorded simultaneously with the video by a gyroscope that is built into the 360° camera. During the presentation, these rotational movements are evaluated and transformed in real-time with respect to the head movements of the observer.

### 3.2 Video Display Framework

For the experiment, we custom-built a video player based on OpenVR which is able to decode and present the single 6k stereo frames (one 6k image per eye) at the recorded video frame rate (30 FPS) and render the output based on the FOV with the frequency of the HMD (90Hz). We did not experience any frame drops throughout the experiment. Furthermore, we required real-time metadata of the content for the GVS, namely the current camera motion properties and the head transformation.

Our video player uses the full potential of the GPU for the video decoding as well as the rendering of the video.

## 4 Experimental Design

We conducted an within-subjects experiment with three sessions per participant to explore the effect of GVS on the perception of 360° videos. While the visual stimuli were the same for all sessions, the GVS was altered. In the control condition, the GVS was inactive at zero current. In the other two conditions the GVS either stimulated the strongest main rotation axis present in the FOV or the actual rotational velocities as seen by the observer. We counterbalanced the order in which the three conditions were shown to the participants. Furthermore, a 48 hours recovery time was maintained between sessions to avoid carry-over effects. The experiment was reviewed and approved by the corresponding ethics committee under the identification number D_2021-06.

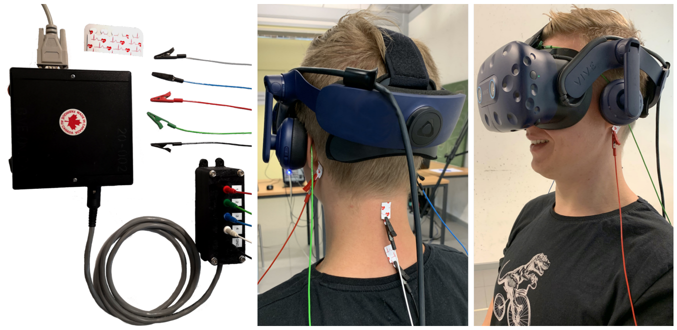

Fig. 3. The GVS device, adhesive electrodes, connector box and electrode cables. On the right, we show its connection with the VR glasses.

### 4.1 Stimuli

#### 4.1.1 Visual Stimuli

In every session, we presented the same 360° video with camera motion in a HMD (see Figure 3). The total runtime of the video is 10 minutes. It shows scenes of walking through a park (moderate movements) followed by a bicycle ride on an uneven road through a forest (fast movements). We chose two different scenarios to determine how GVS affects different modalities. Both scenarios have a presentation duration of five minutes and were played without a gap. In our experiment, participants had no control over the video except that they could change their viewing direction by head movement.

Cinematic panorama videos are known for their high probability to cause CS [22, 53]. In our videos, the sickness induction is supported by the fast camera movements. These movements increase the sensory mismatch that the seated participants perceive [42].

#### 4.1.2 Vestibular Stimulation

We investigated three different conditions: two conditions with GVS to investigate their effects on the perception of a 360° video in VR and a control condition as a comparison:

- CC: control condition without stimulation. The apparatus is still properly connected (electrodes, GVS), but the stimulation is kept at 0 current. We do not inform the participants that one session has no stimulation to not influence their opinion.

- SA: strongest axis condition with GVS. In this condition only the strongest main rotation axis in the FOV is stimulated. This technique is inspired by the work of Cevette *et al.* [8] and also serves as a comparison to the GVS interpolated condition (IN).

- IN: interpolated condition with GVS that stimulates the exact rotation axis visible in the FOV. This condition uses the axis combination mapping from Sec. 3.1. Our goal is to evaluate whether a precise stimulation significantly differs from the strongest axis condition (SA).

The stimulation in both GVS conditions depends on the pre-recorded rotational velocities of the camera in the video. We transform these movements at run-time with the HMD transformation to truly stimulate the rotations as seen by the VR user. Therefore, although the movements of the recording device are pre-captured, the stimulations in our experiment were entirely dynamic and defined at run-time by the participants' posture. We obtained the angular velocities of the camera in the scene by the gyroscope that is built into our recording device. The movements were therefore recorded along with the video.

### 4.2 Apparatus

We recorded the 360° videos with an Insta360 Pro camera [24] at 6*k* stereo resolution (6400 x 6400 px) and 30 FPS. The videos are encoded with the HEVC codec (H265). Gyroscopic data was recorded every 3ms. The 360° camera was mounted on a snowboard helmet to record the scenes since we required fast and flexible movements with hands-free control. The aperture was custom-built and strengthened with extra padding and stabilizers to control the weight of the camera. The final apparatus can be seen in Figure 4.

For the experiment we used a commodity HTC Vive Pro HMD with a FOV of 110° and a frame rate of 90 Hz. The resolution of that HMD is 2880 x 1600 px and therefore renders the full resolution of the video in the respective FOV. All video footage is played with the corresponding audio.

Our GVS device from Good Vibrations Engineering [57] (Canada) has four current outputs and one ground electrode (see Figure 3). The device offers a maximum current of 2.5 mA per electrode. The latency between sending a signal in the application and stimulation to the electrode is less than 15ms. In the experiment, the GVS was controlled by our experiment presentation software. For safety reasons, the device is protected against any unanticipated power transmission by design using battery power and information transmission via air-gapped fiber optics. We use adhesive electrodes with a size of 13x16 mm to attach the GVS to the participants.

### 4.3 Participants

A total of 47 participants completed all three sessions (18 females, Age range = 19-52, Avg age = 24.79, SD = 5.72). Participants were compensated with 30€. The order in which each of the three sessions took place was counterbalanced, with each participant receiving a different order. The experiment followed a full within-subjects design.

For the analysis, we divided the participants into two disjoint groups based on whether they were negatively affected by the virtual experience. The group with individuals perceiving the 360° video as unpleasant consists of 30 participants (13 females, Age range = 19-52, Avg age = 24.8, SD = 6.41). 17 participants (5 females, Age range = 21-36, Avg age = 24.76, SD = 4.24) were not affected by the virtual scene.

### 4.4 Measurement

We used the simulator sickness questionnaire (SSQ) [27] and Slater-Usoh-Steed (SUS) presence questionnaire [47, 54, 55] for participant feedback. Both questionnaires require self-assessment of the participants based on how they feel and how they perceived the scene, respectively. The SSQ is an effective tool to measure CS for 360° videos in VR as demonstrated by Singla *et al.* [46]. Following common procedure, we let participants fill in the SSQ twice, before and after each session of the experiment, to counteract different daily conditions. The total sickness score as well as the corresponding subscores of the SSQ are calculated according to the original procedure of Kennedy *et al.* [27]. The SUS presence questionnaire was filled out once per session, immediately after the experience.

During the experiment we also asked the participants to press the trigger button on the Vive controller every time their comfort feeling got worse, and to press the touchpad when their well-being increased. Based on these responses the participants' individual level of discomfort is calculated. We specifically consider discomfort to not only refer to symptoms of CS but also to any negative effects of the GVS like scratching from the electrodes. Furthermore, the head movements of the participants were recorded.

Effective GVS can be verified by the physical tilt of the body in the direction of the stimulation. However, since in the brain the visual information overwhelms the vestibular information for inconsistencies, a body leaning only occurs with closed eyes or matching information. For evaluation, our participants were asked to rate the strength of the perceived curve lean in the video after each session. The methodology follows the SUS presence questionnaire.

Fig. 4. Left: Helmet carrying the 360° camera to capture the recordings for the experiment. Right: Camera in action.

### 4.5 Procedure

The experiment was divided into three sessions with one experimental condition each (CC, SA, IN). The sessions for each participant were conducted on different days with a pause of two days between sessions to avoid any carry over effects [13, 14, 22, 34].

The experiment started with an informed consent and a demographic questionnaire including factors influencing susceptibility to CS. Also, at the beginning of every session the first SSQ [27] was filled. In all sessions (including the sham session) we then attached the five electrodes. With the electrodes attached we performed a calibration of the participant's individual galvanic stimulation level in the first session. The calibration is necessary to find the maximum current per person that is still comfortable. We found that it is crucial to specify suitable maximum currents as the sensitivity to electric currents highly varies. We performed the calibration in two steps: First, the current was gradually increased with a yaw stimulation at the two electrodes behind the ears. In our experience, these are the most strongly perceived electrodes and with the mapping of the IN the highest currents will occur here (cf. Equ. 1–4). The participants were asked to tell when they noticed any unpleasant feeling from the electrodes. As soon as we found a suitable maximum current, we cross checked the value in a second step where we toggled the current from zero. This sudden current change is typically perceived stronger than a slow change. When the participants still found the chosen current to be tolerable, the maximum was found. Otherwise, we repeated the second step with a lower current. The maximum current served as a scaling factor and was used for both GVS sessions to ensure comparability.

In the experiment, the participants were asked to watch a 360° video in VR and informed that they can quit the experiment at any time in case of severe negative feelings. They sat on a chair and were allowed to freely explore the scene but to remain still with their bodies to avoid negative effects on their immersion. They were asked to press certain VR controller buttons when they noticed any positive or negative change of their well-being. The participants watched a 360° video that was divided into two stages graded by the severity of motion in the video (walking, biking), each with a duration of five minutes (cf. Sec. 4.1.1). In total, the participants spent up to ten minutes in the virtual environment but could voluntarily quit the experiment at an earlier point in time. After the experiment, participants filled in the second SSQ, the SUS presence questionnaire and, in case it was the last session, were asked if they noticed any difference between the sessions and received information on the actual goal of the study.

## 5 Results and Analysis

For the analysis of the experimental results we used factorial mixed repeated-measures ANOVAs with condition as within-subject and gender as between-subjects factor. As post-hoc tests we performed pairwise two-sided dependent t-tests for repeated measures with Bonferroni-

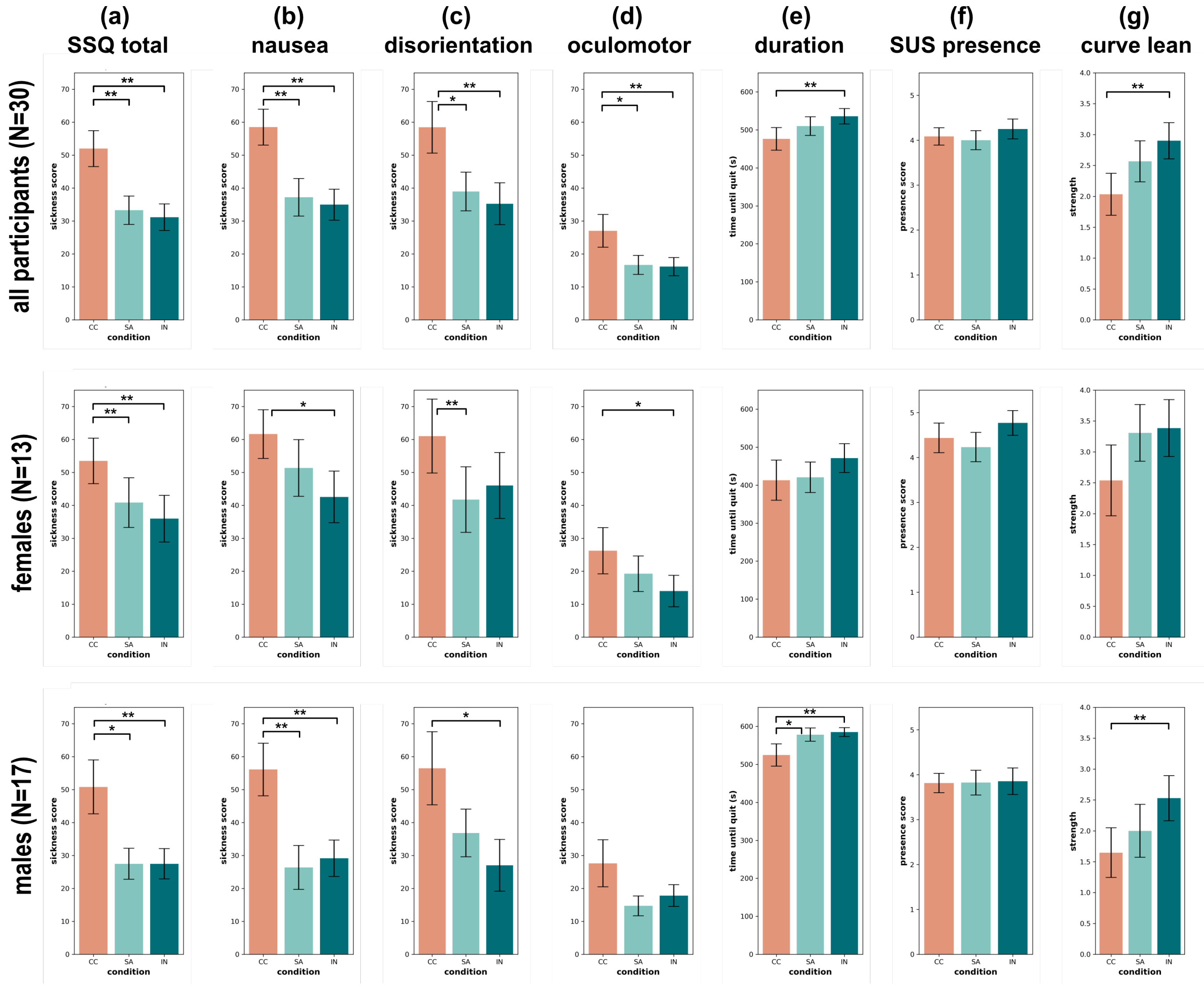


Fig. 5. Averaged SSQ scores, durations and presence results for control condition (CC), strongest axis condition (SA) and interpolated condition (IN). Error bars represent the SEM. **(a)** SSQ results for the total score. **(b-d)** results for each of the SSQ subscales. **(f)** SUS presence questionnaire results. **(e)** duration people were willing to spend in the virtual environment. **(g)** self-indicated score of how much participants felt they were leaning into the curves during the video. Significant results are denoted by '**' ($\mathbf{p \leq 0.016}$, Bonferroni-corrected for multiple comparisons) and '*' ($\mathbf{p \leq 0.05}$).

correction. The time-series data was analyzed with cluster-level permutation tests.

We found that in most cases the participants could be categorized into two groups: people for whom the video had no effect (SSQ score and discomfort close to 0) and those who were strongly affected, at least without GVS. We separated these two groups for the analysis in order to make more concrete statistical statements and to understand the impact of GVS on these two different groups. The total SSQ score served as the classification factor for the groups. When this score was below 20 without GVS, the participant was assigned to the first group (no effect) and vice versa. For the analysis, we particularly focus on the group of participants for whom the video had a strong effect, since the effectiveness of GVS can only be considered when the video caused CS in the first place. For all statistics that account for the unaffected participants this is explicitly stated. However, we also contemplate that GVS can still have a negative effect when people do not get CS from the VR scene. The results of this analysis are described below.

Gender has a strong influence on the susceptibility for CS according to previous research [40]. Consequently, our analysis includes a separate analysis of gender.

During the experiment, 20 participants chose to end one or more of the sessions early because of severe sickness symptoms (42.6%). Most of the terminations were observed during the sham condition with the GVS device deactivated (CC: 31.9%, SA: 25.5%, IN: 25.5%), which is an early indicator that the participants experienced the strongest symptoms in CC. As expected, most participants opted for a termination already during the first session (S1: 38.3%, S2: 25.5%, S3: 19.1%). Therefore, it is most likely that a learning effect occurred. We used a counterbalanced design to act against this learning effect.

Figure 5 illustrates the results of the SSQs, the SUS presence questionnaire results and the average times for participants to end a session. The SSQ was analyzed for its total score and the three subscores of nausea, disorientation and oculomotor [27].

Overall, the results show the same trend for almost all questionnaires as well as the discomfort data: CC is perceived as the most sickness inducing. Both GVS conditions were equally able to reduce the sickness score. For the interpolated 3D GVS we can also see some positive side effects unique to this session: an increased time until participants terminated the session and the highest feeling of comfort.

The analysis shows a significant main effect on the SSQ total

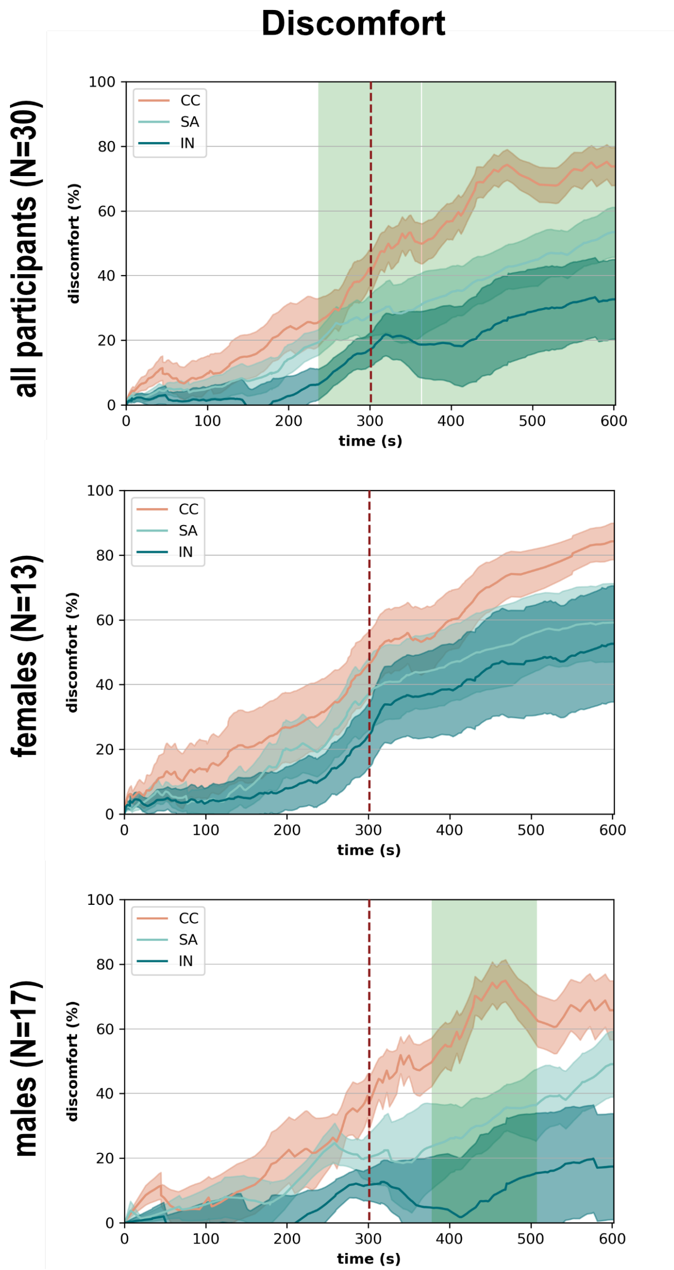


Fig. 6. Relative discomfort over the time of the video ($N_{all} = 30$, $N_f = 13$, $N_m = 17$). Normalized per participant by their highest score in all sessions under consideration of the session times. The shaded areas around the mean line denote the SEM. Sections with significant differences are highlighted with a green background ($\mathbf{p \leq 0.05}$). The red dashed line marks the scenario switch from walking to biking.

score (Figure 5a) for condition ($F(2,87) = 6.12$, $p = 0.0033$). Pair-wise dependent t-tests confirm the significant difference to appear for both GVS conditions when all participants are considered. The difference to CC for the interpolated 3D stimulation was most significant ($T = 3.76$, $p = 0.0008$), but also SA achieved notable results ($T = 3.1$, $p = 0.0043$). A comparable trend as for the overall results can also be found for the single subscores of the SSQ. The nausea subscale of the SSQ (Figure 5b) presents a significant main effect for condition ($F(2,87) = 6.0$, $p = 0.0036$). While IN lowered nausea for both genders ($T > 2.2$, $p < 0.05$), the strongest axis condition varied highly with gender and was only for males significant in difference ($T = 3.62$, $p = 0.0023$). For disorientation a significant reduction of this SSQ cluster was achieved by GVS ($F(2,87) = 3.42$, $p = 0.0371$). Pair-wise dependent t-tests confirm this difference for both, the strongest axis condition ($T = 2.4$, $p = 0.0233$) and interpolated condition ($T = 2.76$, $p = 0.0099$). However, when the genders are considered separately, we see a substantial variation in the effect. While for men, only the interpolated 3D GVS was able to significantly reduce disorientation ($T = 2.31$, $p = 0.0343$), it was the opposite case for women. Females were least affected by disorientation effects with SA applied ($T = 3.01$, $p = 0.0109$). For the oculomotor effects (Figure 5d) a significant main effect for condition is shown by the factorial mixed ANOVA for all participants ($F(2,87) = 2.77$, $p = 0.048$). Again, this SSQ subscale is highly affected by gender. For men, the interference of the oculomotor effects is not significantly changed by the use of GVS. On the other hand, for women the interpolated stimulation (IN) was able to reduce these effects by a meaningful amount ($T = 2.27$, $p = 0.0425$). SA had no effect for both genders. Note, that in general the oculomotor scores are quite low compared with the other subscales of the SSQ.

The results of the duration participants were willing to spend in the 360° video before they chose to end the experiment are shown in Figure 5e. The two conditions had very different effects on the duration participants' stayed in the scene. While IN made the VR users stay significantly longer in the scene ($T = -3.2$, $p = 0.0033$), SA had no such effect. However, the gender is of great importance here: men were willing to spend more time in the virtual scene with either GVS method applied (SA: $T = -2.23$, $p = 0.0408$; IN: $T = -2.78$, $p = 0.0134$). Female participants on the other hand were less affected and without a statistically significant effect for duration. Still, on average, women spent 59 seconds (14%) longer in the 360° video with interpolated GVS. For the results of the SUS presence questionnaire, all sessions led to comparable perceptions of the scene. The use of GVS did not notably change the users' feeling of presence ($F(2,87) = 0.38$, $p = 0.6882$). Also gender showed no effect here. While these presence results remained on the same level, the participants' score for curve leaning did vary. The participants reported scores for physically leaning into the curves they visually observed was significantly improved with interpolated 3D GVS ($T = -2.7$, $p = 0.0114$). These general results were mostly due to the male participants ($T = -2.76$, $p = 0.0139$) and insignificant for women. SA was not able to achieve a statistical improvement of the curve leaning.

Figure 6 shows the results of the overall discomfort over time of the experiment as measured by the controller feedback. The discomfort data is normalized per person by the keystroke responses during the experiment. This self-indicated feeling of discomfort decreases or increases by one unit each time the corresponding keys are pressed. The highest value reached in one of the three sessions weighted by the duration spent in the session is considered to be the maximum global discomfort level for this person across all sessions. The normalization is therefore relative and the maximum value may be perceived differently by each individual. As expected, the discomfort of the participants increases over the time of the experiment. However, the results of the GVS sessions are distinctly different from SHAM and increase at a much slower rate. Especially in the second part of the video with strong movements, a differentiation of the results is noticeable and thus the scenes trigger considerably less discomfort when GVS is applied. The statistical analysis confirms these results and shows a significant difference (shaded areas denote standard error of the mean in Figure 6) for more than half of the video duration and especially for the second part (strong movement).

Although participants felt more comfortable in the GVS session, no difference in their exploratory intention could be determined by their head movement intensity.

For the group of participants that was unaffected by the video, GVS induced no negative effect. For this group all statistical results are insignificant. This finding suggests that VR users unaffected by CS also do not experience adverse effects by GVS. As a result, the applicability of GVS to the general public is greatly increased.

## 6 Discussion

A common way to describe 3D rotations is via the three main rotations of the axes, known as roll, pitch and yaw. Any rotation can be achieved by a concatenation of three rotations around the principal axes (Euler angles). The commonly used bilateral bipolar GVS stimulates the horizontal and vertical canal of the vestibular system simultaneously. As a result a yaw rotation towards the cathode and a simultaneous roll on the same side are perceived. In this stimulation model the canals are always simultaneously stimulated and cannot be disconnected. A pitch rotation is not induced in this model.

Cevette *et al.* [8] proposed the OVR model which allows for a separate stimulation of roll, pitch and yaw. With five electrodes and well-defined stimulation pairs, the rotations around the principle axes are stimulated one at a time. We adapted this type of stimulation (cf. strongest axis condition) for VR use.

However, rotations rarely occur exactly around one principal axis, but rather in the broad spectrum in between. If these rotations are projected onto the nearest principal axis, as in SA, the remaining information is lost. This could also have an effect on the perception by the vestibular system. In theory, the optimal case is a stimulation that relays all information to the vestibular system in exactly the same way as it appears visually. With the second GVS condition (cf. interpolated condition) we present an OVR mapping that we hypothesized to be capable of stimulating all rotational movements of the visual field. The electrode pairs responsible for the stimulation of the principal axes are combined in the mapping, taking into account the correct polarization. Thereby, the influence of the rotational components is weighted by their strength. Hence, if the visual field moves in yaw direction while pitching twice as fast, the mapping stimulates one part of the yaw electrode pair and two parts of the pitch electrode pair.

### 6.1 GVS vs. Sham Stimulation

The experimental results show a clear indication that both GVS techniques successfully reduce CS. In the following, we focus on the participant group that suffered CS symptoms during the experiment. In all sessions the SSQ score approximately dropped by half when GVS was applied. This positive effect occurs not only for the total SSQ score but also for the SSQ subscores of nausea, disorientation and oculomotor effects. But CS is not the only negative effect that was reduced by galvanic stimulation of the vestibular system. In the experiment, the participants indicated all changes of their feeling of comfort via button presses, which allows us to derive a general progression of discomfort over the time of the experiment. Based on this data, a significantly higher feeling of comfort was achieved with the use of GVS. This substantial improvement was present during almost the entire scene with fast movements, but also in large portions of the walking scene. While it stands to reason that the mitigation of CS also contributed to an improvement in the overall comfort feeling, the results also show that no other negative effects arose from the GVS itself. Such negative effects would include, e.g., itching at the electrodes.

These general results show VR to be a valid field of application for the GVS technology. A significant benefit for the reduction of CS is achieved regardless of which of both GVS method is used. The integration of GVS technology into future VR glasses could permanently counteract CS in VR environments. Thereby, the visual stimulus remains unchanged and the vestibular sensation adapts to the virtual experience. GVS is unobtrusive and is effective even with current levels that are only slightly or not at all noticeable to the user. However, this unobtrusiveness requires individual calibration. Unfortunately, calibration has often been missing in previous work. This work has shown the importance of customizing the current intensity to the user's personal preference.

### 6.2 Strongest Axis Stimulation vs. Interpolated Currents

While both GVS conditions outperformed CC, they were not equal in their overall effect. Although CS was at the same level in both GVS sessions, the participants chose to stay longer in the scene with interpolated stimulation. This significant increase of the session duration is unique to IN in our experiment. From the results of the SUS questionnaires we could not infer a change in the feeling presence with GVS. Interestingly, most of the participants mentioned a different feeling between sessions in the open interview after the experiment. Without any knowledge of the actual procedure, they mentioned to "feel the movements in the video, even when the head is static" and that "[the GVS sessions] felt like a realistic dream, instead of a bad video". A difference is also evident in the results for perceived curve leaning. For the IN session, participants perceived a significantly stronger desire to physically lean into curves they watched in the HMD. Given these subjective user reports, it should not be rejected that GVS can, in a certain way, intensify the presence of VR users. However, further research is needed to understand this connection in detail.

As described above, we also investigated the progression of participants' overall comfort levels during the three VR sessions. Both 3D GVS methods were shown to be effective techniques to reduce discomfort. In a direct comparison of SA and IN, we can see that IN is always slightly below SA on average. However, a significant difference between the two sessions is only present in the last third of the walking sequence. Furthermore, for male participants, the flatter progression of IN shows a diverging development towards the end of the video.

Altogether, the presented interpolated mapping based on OVR is a promising method to compensate CS and improve the overall user experience. With this method, users were willing to stay longer in the scene while feeling more comfortable. With interpolated 3D stimulation, we aimed to represent all rotational movements of the visual field equally on the vestibular canals, thus significantly minimizing the visual-vestibular mismatch. We were particularly interested in how precise stimulation of intermediate axes differs from the method of strongest main axis stimulation. With the aforementioned differences, using interpolated stimulation is particularly useful whenever CS improvement is not the only objective. However, since all aspects of user experience are a fundamental part of almost every VR scene, we are convinced that the presented interpolated 3D mapping for precise stimulation of 3D rotations could find general applicability.

Nevertheless, CS and discomfort were not completely prevented. On the one hand, this may be attributed to the uncompensated linear accelerations. Linear accelerations cause CS to a lesser extent than rotational movements and the movements in our video had mostly a constant velocity [22, 29]. Still, residual accelerations may have caused some CS in the participants. Furthermore, it is likely that due to a general tendency to motion sickness in real life, some participants also experienced CS when the scenarios felt real to them.

### 6.3 Influence of Gender

VR experiences are subject to a general gender bias as noted in previous research [20, 39]. In line with these findings, we found major differences in the impact of our GVS methods when comparing men and women. While GVS is certainly able to reduce CS independent of gender, the scores for men exposed to GVS are significantly lower. This is particularly true for SA. Without GVS, both genders experienced the same level of CS. The differentiation is even stronger for the nausea subscores of the SSQ. GVS was able to drastically reduce nausea, especially in men, after similar baseline results in SHAM. It is also worth mentioning that the CS triggered by the video in our experiment was perceived to be equally strong for men and women. The time the participants were willing to spend in the virtual environment until they became too uncomfortable is again affected by gender. Male participants were willing to stay significantly longer in the scene as soon as GVS was applied. For females, there was no significant change in duration. These results are especially interesting considering that the males perceived lower CS despite the longer duration of the experiment. The comfort levels also evolved more positively for male participants than for females using the GVS device. In particular the second part of the video (with strong movements) made male participants feel significantly more comfortable with GVS. It is likely that these results are related to the already lower CS scores of the males.

Consequently, when comparing men and women for moving camera 360° videos, a stimulation of the galvanic system may be most effective for male VR users. Also, for female participants, we found a significantly positive impact of the overall experience, levelling the field in terms of gender-based CS susceptibility. However, these results are given under consideration of the relatively small groups of participants per gender and may need further verification.

All of the results above consider the group of people for whom the video caused negative effects. When people use VR without any signs of CS, no mitigation is necessary. However, we investigated whether GVS would have a negative effect in this case. With the use of GVS, our results show no increase in CS severity for these individuals and also the comfort levels remain the same. With these results, we conclude that regardless of the user, GVS has either a positive effect when needed, or no effect otherwise.

### 6.4 Impact of the Scenarios and Generalizability

In the stimulus video, two scenarios are shown. The first sequence is a walk through a park in summer. In this scenario the camera moves around a few curves and there are also slight head turns. The speed is moderate but constant. The second part of the video is shot from the perspective of a mountain biker who is riding at high speed down a forest path. The path itself contains a lot of curves and fast head turns of the rider in pitch and yaw direction. Roll is represented mainly by the curve leaning.

Unfortunately, it is hard to determine how much each scenario contributed to the resulting CS. For this separation, another SSQ would be required after the first sequence. However, any interruption of the video breaks the presence of the participants. Consequently, we compare the two scenarios mainly on the basis of the discomfort measurements. From the oral feedback of the participants, biking was, as expected, perceived to be significantly more sickness-inducing than walking. When considering that the participants were already affected by the walking sequence at the beginning of the second scenario, the discomfort level increases comparably in both parts of the video. The main difference is in the increase of the values: in the walking scenario, the discomfort score first grows slowly and gradually increases from halftime onward. In the last section of the walking scenario, where the GVS achieves significant improvements, the video shows a sequence of walking down stairs. This part was perceived as very unpleasant by most of the participants, but could be compensated effectively with GVS. In the biking scenario, the discomfort level increases constantly, but with distinct peaks where the movements in the video were very fast. These peaks are absent in the GVS sessions and the discomfort level increases only slightly in the second part.

A generalization for usability of GVS for other 360° videos is expected, given that our video shows many natural rotations in all directions and is presented for different scenarios. However, such a generalization does not necessarily apply to computer generated scenes. In principle, a mitigation is accomplished by reducing the mismatch between perceived motion from different sources (visual, vestibular). The motion in the visual is reflected by the optical flow of the frames. In computer-generated content, the optical flow is comparable to that in real-world footage, but with fewer disturbances, as the influencing factors remain under full control. Accordingly, an effective use of GVS to mitigate CS in computer generated video-like content (little linear motion of the user) is very probable. In this sense, we would like to reinforce the importance of real-world videos in our experiment. Compared to fully controllable generated content, they incorporate some *real world complexity* (imperfect pixels, unpredictable events). Once this complexity can be controlled with the GVS, it is trivial to achieve an effect with generated content. But this is not necessarily applicable the other way around. For virtual interactive worlds, however, a generalization is more difficult, as these additionally involve linear motions of the user. Unexpected interactions may occur between the two motion sources (linear and rotational motion). Still, other works in the field of redirected walking with GVS already show that the use of GVS can be an effective and useful extension in interactive scenes [30, 49].

### 6.5 Experimental Modalities

The duration of the video in the experiment was ten minutes in total, which is probably shorter than a typical VR session. We chose this rather short time because our 360° video is sickness inducing by design and therefore has a high probability to cause CS. Any longer duration was considered to become unethical. We chose strong scenarios to have a better control over the experimental variables, i.e., to increase the group of participants that are affected by CS. With the two scenarios, people are more likely to be affected by the video at some point during the exposure time, regardless of their susceptibility to CS.The capability of our videos to cause CS is further demonstrated by the number of participants leaving the experiment early (20).

For our video we used a gyroscope to capture the rotational movements of the video recordings. Most 360° cameras are equipped with a built-in gyroscope, mainly used for image stabilization. The prerequisite for this kind of metadata is therefore usually given for own recordings. It is more difficult when videos from the Internet are used, as there is usually no motion data available for these recordings. Analytical methods or artificial neural networks can be used to infer the background movements of arbitrary video. In particular, feature detection and quaternion matching or smoothed optical flow promise a reliable calculation of the rotations on existing material [12, 23, 38]. However, this is outside the scope of this work.

### 6.6 Ethical Considerations

According to current scientific knowledge GVS is considered safe given a moderate current (2.5mA or smaller) and healthy participants [5, 56]. Most interesting, regarding adverse effects of current stimulation of the brain is the work of Brunoni *et al.* [5]. They analysed over 200 studies for tDCS, a superset of GVS, with a total of 3836 participants. They found that “type of adverse events is mild and frequency of them in tDCS studies is low”. No serious adverse event occurred. However, this primarily concerns short-term stimulation. Throughout our work, we could not observe any contrary effects. All effects were temporary (minor localized irritation of the skin, initial low disorientation symptoms) and resolved quickly after the stimulation. Nevertheless, GVS should be used with caution. All of our experiments involved only a short stimulation ($\leq 10$ min) and were conducted in strict accordance with ethical guidelines under the supervision of the ethics committee and were previously approved by a physicist with proven expertise on the field. The effect of stimulation over longer periods (several hours) and frequent use may need further investigation.

## 7 Conclusion

In this work, we investigate 3D GVS to induce the sensation of rotation in arbitrary direction. Our galvanic stimulation is based on the OVR model and implemented to stimulate either only the strongest visual motion axis of roll, pitch and yaw, or precise intermediate rotations. Removing the visual-vestibular mismatch for rotational motions is essential, since they are the main factor responsible for inducing CS [22]. This importance is confirmed by the results of our experiment, where over half of the initial CS was removed and the users' feeling of comfort significantly increased with the applied GVS methods.

Furthermore, we revealed that the application of GVS makes a difference to its effect. Whereas both methods, strongest axis stimulation and interpolated 3D GVS, successfully mitigated CS, the here introduced precise stimulation of intermediate axes has further positive effects. With this method, participants are willing to spend more time in the VR scene. At the same time they experienced the lowest level of discomfort with interpolated currents.

Comparing both genders, both GVS methods yield considerably better results for men while also significantly increasing the feeling of comfort for female participants. After the same initial values for the control session, GVS reduced the CS scores and the time spent in the session increased by a large margin. Nevertheless, both men and women took advantage of the stimulation.

Our results raise the confidence that 3D GVS offers a meaningful extension for VR applications that is able to achieve significant improvements of the virtual experience. Nevertheless, this work does not necessarily prove that all rotations of the visual field are fully mapped onto the vestibular system by our interpolation as initially suggested by our small empirical pre-experiment. Since we now demonstrated the practicality of our approach, our future work will focus on the precision of this mapping and further improvements of the GVS application in virtual reality.

## Acknowledgments

The authors gratefully acknowledge funding by the German Science Foundation (DFG MA2555/15-1 “Immersive Digital Reality”).


## References


[1] I. B. Adhanom, N. N. Griffin, P. MacNeilage, and E. Folmer. The effect of a foveated field-of-view restrictor on vr sickness. In *IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 645–652. IEEE, 2020.

[2] K. Aoyama, H. Iizuka, H. Ando, and T. Maeda. Four-pole galvanic vestibular stimulation causes body sway about three axes. *Scientific reports*, 5:10168, 2015.

[3] P. Bala, D. Dionísio, V. Nisi, and N. Nunes. Visually induced motion sickness in 360° videos: Comparing and combining visual optimization techniques. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 244–249. IEEE, 2018.

[4] P. Bala, I. Oakley, V. Nisi, and N. Nunes. Staying on track: a comparative study on the use of optical flow in 360 video to mitigate vims. In *ACM International Conference on Interactive Media Experiences*, pp. 82–93, 2020.

[5] A. R. Brunoni, J. Amadera, B. Berbel, M. S. Volz, B. G. Rizzerio, and F. Fregni. A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation. *International Journal of Neuropsychopharmacology*, 14(8):1133–1145, 2011.

[6] P. Budhiraja, M. R. Miller, A. K. Modi, and D. Forsyth. Rotation blurring: use of artificial blurring to reduce cybersickness in virtual reality first person shooters. *arXiv preprint arXiv:1710.02599*, 2017.

[7] R. Byrne, J. Marshall, and F. Mueller. Balance ninja: towards the design of digital vertigo games via galvanic vestibular stimulation. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pp. 159–170, 2016.

[8] M. J. Cevette, J. Stepanek, D. Cocco, A. M. Galea, G. N. Pradhan, L. S. Wagner, S. R. Oakley, B. E. Smith, D. A. Zapala, and K. H. Brookler. Oculo-vestibular recoupling using galvanic vestibular stimulation to mitigate simulator sickness. *Aviation, space, and environmental medicine*, 83(6):549–555, 2012.

[9] F. Danieau, J. Fleureau, A. Cabec, P. Kerbiriou, P. Guillotel, N. Mollet, M. Christie, and A. Lécuyer. Framework for enhancing video viewing experience with haptic effects of motion. In *2012 IEEE Haptics Symposium*, pp. 541–546, 2012.

[10] B. Day, A. Severac Cauquil, L. Bartolomei, M. Pastor, and I. Lyon. Human body-segment tilts induced by galvanic stimulation: a vestibularly driven balance protection mechanism. *The Journal of physiology*, 500(3):661–672, 1997.

[11] P. DiZio and J. Lackner. Circumventing side effects of immersive virtual environments. *Advances in human factors/ergonomics*, 21:893–896, 1997.

[12] D. D. Doyle, A. L. Jennings, and J. T. Black. Optical flow background estimation for real-time pan/tilt camera object tracking. *Measurement*, 48:195–207, 2014.

[13] E. Ebrahimi, B. Altenhoff, L. Hartman, A. Jones, S. Babu, C. Pagano, and T. Davis. Effects of visual and proprioceptive information in visuomotor calibration during a closed-loop physical reach task in immersive virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 103–110, 2014.

[14] E. Ebrahimi, B. Altenhoff, C. Pagano, and S. Babu. Carryover effects of calibration to visual and proprioceptive information on near field distance judgments in 3d user interaction. In *IEEE Symposium on 3D User Interfaces*, pp. 97–104. IEEE, 2015.

[15] M. Elwardy, H.-J. Zepernick, Y. Hu, T. M. C. Chu, and V. Sundstedt. Evaluation of simulator sickness for 360° videos on an hmd subject to participants' experience with virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 477–484. IEEE, 2020.

[16] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In *IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 201–210. IEEE, 2016.

[17] R. Fitzpatrick, D. Burke, and S. C. Gandevia. Task-dependent reflex responses and movement illusions evoked by galvanic vestibular stimulation in standing humans. *The Journal of physiology*, 478(2):363–372, 1994.

[18] C. Fujimoto, Y. Yamamoto, T. Kamogashira, M. Kinoshita, N. Egami, Y. Uemura, F. Togo, T. Yamasoba, and S. Iwasaki. Noisy galvanic vestibular stimulation induces a sustained improvement in body balance in elderly adults. *Scientific reports*, 6(1):1–8, 2016.

[19] L. Galvani. De viribus electricitatis in motu musculari commentarius. 1791.

[20] S. Grassini and K. Laumann. Are modern head-mounted displays sexist? a systematic review on gender differences in hmd-mediated virtual reality. *Frontiers in Psychology*, 11, 2020.

[21] C. Groth, J.-P. Tauscher, N. Heesen, S. Castillo, and M. Magnor. Visual techniques to reduce cybersickness in virtual reality. In *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 486–487, 2021.

[22] C. Groth, J.-P. Tauscher, N. Heesen, S. Grogorick, S. Castillo, and M. Magnor. Mitigation of cybersickness in immersive 360°videos. In *IEEE Virtual Reality Workshop on Immersive Sickness Prevention (WISP)*, pp. 169–177. IEEE, 2021. doi: 10.1109/VRW52623.2021.0

[23] B. K. Horn. Closed-form solution of absolute orientation using unit quaternions. *Josa a*, 4(4):629–642, 1987.

[24] Insta360 pro. `https://www.insta360.com/product/insta360-pro`. Accessed: 2021-11-26.

[25] J. Irwin. The pathology of sea sickness. *The Lancet*, 118(3039):907–909, 1881.

[26] R. S. Kennedy, J. Drexler, and R. C. Kennedy. Research in visually induced motion sickness. *Applied ergonomics*, 41(4):494–503, 2010.

[27] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3(3):203–220, 1993. doi: 10.1207/s15327108ijap0303_3

[28] H. G. Kim, H.-T. Lim, S. Lee, and Y. M. Ro. Vrsa net: Vr sickness assessment considering exceptional motion for 360° vr video. *IEEE transactions on image processing*, 28(4):1646–1660, 2018.

[29] J. Kim, S. Palmisano, W. Luu, and S. Iwasaki. Effects of linear visual-vestibular conflict on presence, perceived scene stability and cybersickness in the oculus go and oculus quest. *Frontiers in Virtual Reality*, 2:42, 2021.

[30] E. Langbehn, F. Steinicke, P. Koo-Poeggel, L. Marshall, and G. Bruder. Stimulating the brain in vr: Effects of transcranial direct-current stimulation on redirected walking. In *ACM Symposium on Applied Perception*, 2019.

[31] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56, 2000.

[32] A. Lawther and M. Griffin. A survey of the occurrence of motion sickness amongst passengers at sea. *Aviation, space, and environmental medicine*, 59(5):399–406, 1988.

[33] K. Lim, J. Lee, K. Won, N. Kala, and T. Lee. A novel method for vr sickness reduction based on dynamic field of view processing. *Virtual Reality*, pp. 1–10, 2020.

[34] Y.-X. Lin, R. Venkatakrishnan, R. Venkatakrishnan, E. Ebrahimi, W.-C. Lin, and S. V. Babu. How the presence and size of static peripheral blur affects cybersickness in virtual reality. *ACM Trans. Appl. Percept.*, 17(4), Nov. 2020. doi: 10.1145/3419984

[35] T. Maeda, H. Ando, and M. Sugimoto. Virtual acceleration with galvanic vestibular stimulation in a virtual reality environment. In *Proceedings of IEEE Conference of Virtual Reality*, pp. 289–290, 2005.

[36] M. McGill, A. Ng, and S. Brewster. I am the passenger: how visual motion cues can influence sickness for in-car vr. In *Proceedings of the 2017 chi conference on human factors in computing systems*, pp. 5655–5668, 2017.

[37] S. T. Moore, V. Dilda, and H. G. MacDougall. Galvanic vestibular stimulation as an analogue of spatial disorientation after spaceflight. *Aviation, space, and environmental medicine*, 82(5):535–542, 2011.

[38] M. Muja and D. G. Lowe. Fast approximate nearest neighbors with automatic algorithm configuration. *VISAPP*, 2(331-340):2, 2009.

[39] J. Munafo, M. Diedrick, and T. A. Stoffregen. The virtual reality head-mounted display oculus rift induces motion sickness and is sexist in its effects. *Experimental brain research*, 235(3):889–901, 2017.

[40] D. G. Narciso, M. Bessa, M. C. Melo, A. Coelho, and J. Vasconcelos-Raposo. Immersive 360° video user experience: impact of different variables in the sense of presence and cybersickness. 2019.

[41] M. A. Nitsche, P. S. Boggio, F. Fregni, and A. Pascual-Leone. Treatment of depression with transcranial direct current stimulation (tdcs): a review. *Experimental neurology*, 219(1):14–19, 2009.

[42] J. T. Reason and J. J. Brand. *Motion sickness.* Academic press, 1975.

[43] R. J. Reed-Jones, J. G. Reed-Jones, L. M. Trick, and L. A. Vallis. Can galvanic vestibular stimulation reduce simulator adaptation syndrome? 2007.

[44] H. Rheingold. *Virtual reality: exploring the brave new technologies*.

Simon & Schuster Adult Publishing Group, 1991.

[45] C. Sherman. Motion sickness: review of causes and preventive strategies. *Journal of travel medicine*, 9(5):251–256, 2002.

[46] A. Singla, S. Göring, D. Keller, R. R. Ramachandra Rao, S. Fremerey, and A. Raake. Assessment of the simulator sickness questionnaire for omnidirectional videos. In *IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 198–206, 2021.

[47] M. Slater, J. McCarthy, and F. Maringelli. The influence of body movement on subjective presence in virtual environments. *Human factors*, 40(3):469–477, 1998.

[48] B. Song, P. Wen, T. Ahfock, and Y. Li. Numeric investigation of brain tumor influence on the current distributions during transcranial direct current stimulation. *IEEE transactions on biomedical engineering*, 63(1):176–187, 2015.

[49] M. Sra. Steering locomotion by vestibular perturbation in room-scale vr. In *IEEE Virtual Reality*, pp. 405–406, 2017.

[50] M. Sra, A. Jain, and P. Maes. Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In *Proceedings CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2019.

[51] M. Sra, X. Xu, and P. Maes. Galvr: a novel collaboration interface using gvs. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, pp. 1–2, 2017.

[52] K. M. Stanney, R. S. Kennedy, and J. M. Drexler. Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 41(2):1138–1142, 1997. doi: 10.1177/107118139704100292

[53] J.-P. Tauscher, A. Witt, S. Bosse, F. W. Schottky, S. Grogorick, S. Castillo, and M. Magnor. Exploring neural and peripheral physiological correlates of simulator sickness. *Computer Animation and Virtual Worlds*, 2020.

[54] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr. Walking¿ walking-in-place¿ flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pp. 359–364, 1999.

[55] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence*, 9(5):497–503, 2000.

[56] K. S. Utz, V. Dimova, K. Oppenländer, and G. Kerkhoff. Electrified minds: Transcranial direct current stimulation (tdcs) and galvanic vestibular stimulation (gvs) as methods of non-invasive brain stimulation in neuropsychology—a review of current data and future implications. *Neuropsychologia*, 48(10):2789–2810, 2010.

[57] Good vibrations engineering: Gvs. `https://goodvibrationsengineering.com/GVS.html`. Accessed: 2021-09-04.

[58] S. Weech, J. Moon, and N. F. Troje. Influence of bone-conducted vibration on simulator sickness in virtual reality. *PLOS ONE*, 13:1–21, 03 2018.

[59] S. Weech, T. Wall, and M. Barnett-Cowan. Reduction of cybersickness during and immediately following noisy galvanic vestibular stimulation. *Experimental Brain Research*, 238(2):427–437, 2020.