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A Review of Electrostimulation-based Cybersickness Mitigations

Gang Li *
School of Pyschology, School of Computing Science
University of Glasgow
Glasgow, UK
Gang.Li@glasgow.ac.uk

Mark McGill
School of Computing Science
University of Glasgow
Glasgow, UK
Mark.McGill@glasgow.ac.uk

Stephen Brewster
School of Computing Science
University of Glasgow
Glasgow, UK
Stephen.Brewster@glasgow.ac.uk

Frank Pollick
School of Pyschology
University of Glasgow
Glasgow, UK
Frank.Pollick@glasgow.ac.uk

Abstract— **With the development of consumer virtual reality (VR), people have increasing opportunities to experience cybersickness (CS) — a kind of visually-induced motion sickness (MS). In view of the importance of CS mitigation (CSM), this paper reviews the methods of electrostimulation-based CSM (e-CSM), broadly categorised as either "VR-centric" or "Human-centric". "VR-centric" refers to approaches where knowledge regarding the visual motion being experienced in VR directly affects how the neurostimulation is delivered, whereas "Human-centric" approaches focus on the inhibition or enhancement of human functions per se without knowledge of the experienced visual motion. We found that 1) most e-CSM approaches are based on visual-vestibular sensory conflict theory — one of the generally-accepted aetiologies of MS, 2) the majority of e-CSM approaches are vestibular system-centric, either stimulating it to compensate for the mismatched vestibular sensory responses, or inhibiting it to make an artificial and temporary dysfunction in vestibular sensory organs or cortical areas, 3) Vestibular sensory organ-based solutions are able to mitigate CS with immediate effect, while the real-time effect of vestibular cortical areas-based methods remains unclear, due to limited public data, 4) Based on subjective assessment, VR-centric approaches could relieve all three kinds of symptoms (nausea, oculomotor, and disorientation), which appears superior to the human-centric ones that could only alleviate one of the symptom types or just have an overall relief effect. Finally, we propose promising future research directions in the development of e-CSM.**

Keywords—virtual reality, cybersickness, mitigation, galvanic vestibular stimulation, transcranial direct current stimulation

I. INTRODUCTION

Sensory conflict theory (SCT) is one of the generally-accepted aetiologies of motion sickness (MS) [1]. Imagine that our brain is a visually impaired person who needs the help of two friends to cross the road. If friend A tells them to turn right, while friend B tells them to turn left, then the blind person will get confused. If friend A is our visual system and friend B is the vestibular system, then the mismatched inputs between the two systems leads to a form of neurological confusion – referred to as sensory conflict - and accordingly may result in symptoms including cold sweating, headache, nausea, oculomotor disturbances, disorientation and so on [2].

Virtual Reality (VR) users may develop symptoms similar to MS, a malady called cybersickness (CS) [3]. The term CS was first used by McCauley & Sharkey in 1992. They delineated it as a special MS that was triggered by visually-induced illusory self-motion, namely vection, in a virtual environment ("cyberspace"), referred to also as Visually Induced Motion Sickness (VIMS). Although a precise reason why we experience CS is somewhat lacking, it is generally accepted that SCT is one of aetiologies of CS. That is, CS occurs when vection is not matched by corresponding vestibular information (that is, there is an absence of actual responses from vestibular sensory organs: otoliths and/or semi-circular canals). The fundamental difference between CS and MS is that CS occurs strictly with visually-induced visual-vestibular mismatch, while for MS, usually both vestibular and visual systems can be contributing factors [4]. In the context of consumer VR, many applications that involve moving visual surroundings (e.g., self-locomotion, virtual rollercoasters, and other simulated motions such as driving a vehicle or experiencing flight) may elicit vection and trigger CS.

A straightforward solution to mitigate CS is to ensure that all perceived self-motion in VR is enacted physically (e.g., physically walking in roomscale environments, or using a mechanical chair that rotates with synchronized motions in VR scene [5]). However, such approaches are not always preferable, with physical movement requiring both effort and space, and locomotion techniques impacting the accessibility of VR applications. For example, if consumers use VR in transportation [6], [7], there is little-to-no ability to generate physical motions matching what is being experienced in VR – at-best, we might map self-motion to vehicle motion (the approach used by [6], [7]), but this heavily restricts our ability to move freely in VR.

In order to mitigate CS in a simple way, methods of electrostimulation-based CS mitigation (e-CSM) have been proposed [8]. Thus, the goal of this paper is to review e-CSM, answering the following research questions (RQ1 to RQ5).

- RQ1: What techniques have been used for e-CSM?

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*corresponding author: G. Li; e-mail: lixiaogang110217@hotmail.com.

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- RQ2: What theoretical underpinnings do these techniques have?
- RQ3: What aetiologies are these theoretical underpinnings based on?
- RQ4: How do these approaches differ based on reliability?
- RQ5: Which techniques are best suited to real-life application?

To facilitate the review, the e-CSM methods are organized into a tree-structure taxonomy (as shown in Figure 1), which consists of two main categories, namely "VR-centric" and "human-centric". "VR-centric" refers to approaches where knowledge regarding the visual motion being experienced in VR directly affects how the neurostimulation is delivered. This can be for any experience with visual motion e.g. using immersive VR headsets, or desktop/monitor VR. Conversely, "Human-centric" approaches are to some extent like digitalized MS pills which focus on neurostimulation for the inhibition or enhancement of human functions (e.g. the vestibular system) without knowledge of the specific visual motion being experienced. For each category, we reviewed three aspects, namely "theoretical underpinnings", "practical utility", "reliability". For "theoretical underpinnings", we studied why e-CSM is effective. Regarding "reliability", we focused on the variety of mitigated effects in different e-CSM conditions. For "practical utility", we aimed to discuss the possibilities for real-life applications and deployment. The fundamental difference between current work and previous reviews on CS [9], [10] is that we focus on the potential of e-CSM approaches specifically, summarising recent advances.

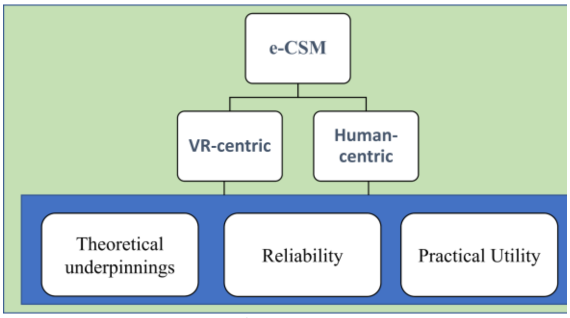

Fig 1. Hierarchical taxonomy for e-CSM approaches

II. Methods and Materials

Our search used various data sources, including the Institute of Electrical and Electronics Engineers Xplore, Association for Computing Machinery Digital Library, ScienceDirect, and SpringerLink. The exclusion criteria were traditional MS studies and non-electrostimulation studies, such as mechanical vibration-based bone conductance vibration [11]. The inclusion criteria were e-CSM-specific publications found by using the following sets of search items in the field of title, abstract and key words in the past decade (2010-2020).

- "galvanic stimulation" and ["sickness" or "cybersickness"];
- "transcutaneous stimulation" and ["sickness" or "cybersickness"].
- "transcranial stimulation" and ["sickness" or "cybersickness"].

The reason we separated "sickness" from "cybersickness" was to search related papers as much as possible, since a great variety of terminologies have been used, including VR sickness and simulator sickness [2], [12]–[14].

III. Results

Searches identified ten records that met the inclusion criteria. As shown in Fig. 2, according to the theoretical underpinnings, these e-CSM approaches can be classified into three types: 1) mitigating CS by compensatory vestibular responses, including directional galvanic vestibular stimulation (d-GVS), galvanic cutaneous stimulation (GCS); and 2) mitigating CS by direct inhibitory effects on vestibular sensory organs, such as high-frequency noisy GVS (i-GVS), and on vestibular cortical areas, such as cathodal transcranial direct current stimulation (tDCS) or indirect inhibitory effect on cortical areas, such as anodal tDCS, and 3) mitigating CS by enhanced postural control ability on neck, such as transcutaneous electrical nerve stimulation (TENS). From the perspective of application, all compensatory solutions are VR-centric, while other solutions are human-centric. The success of these compensatory and inhibitory e-CSM approaches support that SCT may indeed be one of aetiologies of CS, while the effectiveness of TENS seems can be explained from the perspective of postural instability theory (PIT)-based aetiology [15].

A. *Compensatory VR-centric Mitigation*

1) *d-GVS*

The d-GVS uses direct current [8], [16] or low-frequency noisy current (0.02-10Hz) [17] to stimulate vestibular sensory organs so that real (when users are standing) or illusory (when users are sitting) head movement and corresponding body sway can be induced [18]. Prior to experiments, researchers typically increase the current intensity from a very small value until the individual indeed feels illusory head rotation [8], [16]. The minimum current intensity that is able to induce illusory head rotation is called the personalized current intensity (PCI). The d-GVS usually uses one anodal and one cathodal electrode, which are placed on the left and right mastoid process respectively. When electric current flows from anodal to cathodal electrode, the head will be induced to turn from the direction of cathodal electrode to the direction of anodal electrode. In order to induce head rotation about all three axes (pitch, raw and roll), the number of electrodes can be as many as four (left mastoid process, right mastoid process, left forehead and right forehead) [19].When d-GVS is carried out simultaneously with the onset of a moving visual surroundings in VR, users will perceive the electric current-induced rotation immediately, thus the absent vestibular responses can be compensated and the CS can be mitigated. For example, d-GVS can enable the delivery of current stimulation during a

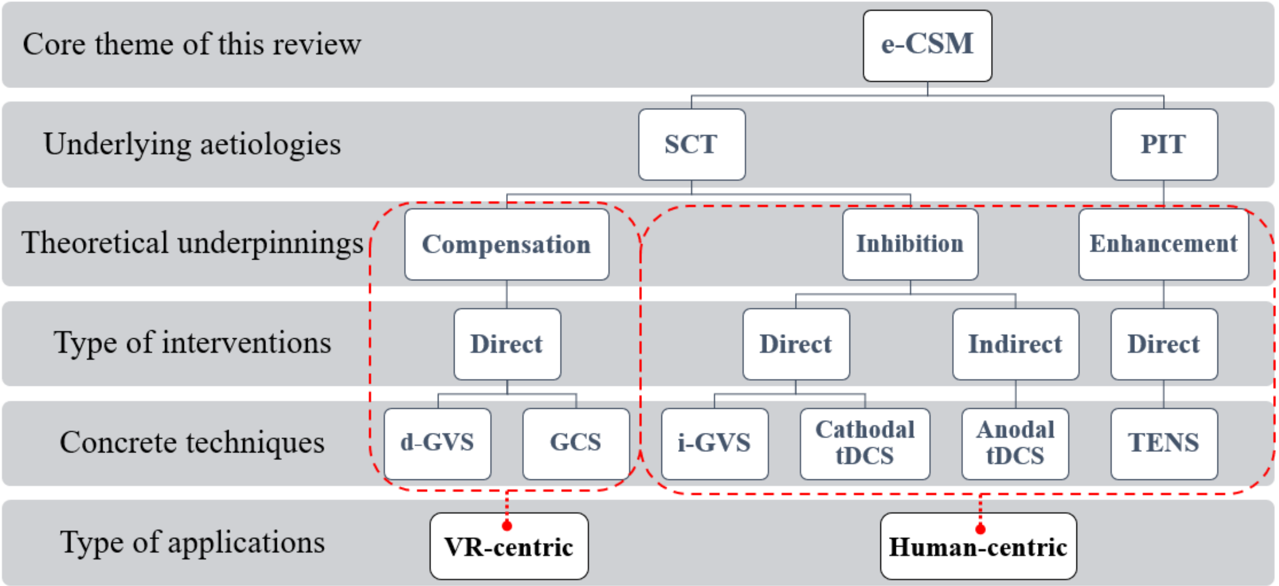

Fig 2. Overview of the current state-of-the-art e-CSM approaches

virtual rollercoaster ride with pre-configured PCI e.g. supporting rollercoaster turns as long as 6 seconds [8].

2) GCS

The GCS is a variant of d-GVS. The differences between them are 1) GCS's electrodes are moved from mastoid processes down slightly to sternocleidomastoids that contain many motor nerves [20], 2) GCS induces real movements only and no illusory movements [12], [21].

B. Human-centric Mitigation

Unlike VR-centric solutions, the electric current in human-centric approaches is delivered during the whole VR experience without any requirement on VR-specific delivering timing.

1) i-GVS

The i-GVS uses higher frequency noisy current. The noisy current mentioned here can be frequency-fixed or -randomized as long as the mean amplitude is zero [22], [23]. Since i-GVS does not induce any movement, the number of electrodes is just two, placed on the left and right mastoid process respectively. The i-GVS approaches are based on the hypothesis of dynamic multisensory reweighting [10]. That is, our brain makes decisions by optimizing multisensory signals if sensory conflicts exist. If we denote the weights and inputs on visual and vestibular system as (W_1 , S_1) and (W_2 , S_2), and denote noisy and raw vestibular inputs as (S_n , S_r), then we can define the integrated inputs X as $X=W_1*S_1 + W_2*S_2$, where $S_2= S_r + S_n$. Based on the signal reliability, the weights can be adjusted (reweighted). The more reliable the input sensory signal is, the more weight will be given (that is, up-weighting); on the contrary, less weight will be given (that is, down-weighting). Therefore, i-GVS's function is to reduce W_2 by increasing S_n so that visual inputs S_1 can be predominant. Certain deaf people (S_2=0) are an extreme example of visual-vestibular information reweighting mechanism, whose S_1 is predominant by nature so that they are rendered immune to MS [24].

2) tDCS

The tDCS is a non-invasive electrical brain stimulation technique that modulates underlying cortical excitability [25]. Depending on whether anodal or cathodal stimulation is applied, tDCS increases or decreases cortical excitability, respectively [25]. According to previous findings that motor and cognitive activities during tDCS might interfere with, or abolish stimulation effects [26], users are suggested to keep still during stimulation. In 2015, Arshad et al. confirmed the feasibility of using cathodal tDCS to inhibit vestibular cortical area (parieto-insular vestibular cortex, PIVC) under traditional MS conditions [27], [28]. However, we did not find any similar studies in VR condition. In 2018, Takeuchi et al. successfully mitigated CS using anodal tDCS on the temporoparietal junction (TPJ) [29]. Unlike PIVC which processes vestibular information, TPJ is believed to process combined visual and vestibular information [28], [29]. Although the precise reason behind this successful case in TPJ remains unclear, it is possible that the vestibular information is indirectly down-weighted by up-weighted visual information in anodal tDCS condition, according to the information reweighting mechanism mentioned above. In a more recent study, anodal tDCS was used to actively enhance the cognitive cortical area (prefrontal cortex) and indirectly suppress the vestibular system [30].

3) TENS

The TENS is a non-invasive alternating current cervical spine stimulation technique that was found to be effective in mitigating both MS and CS when the frequency was set at 100Hz [31], [32]. For each user, a PCI-like mechanism was used to keep the current intensity just below a painful sensation. The electrodes were placed at the midline posterior nuchal region (1.5 cm lateral to the seventh cervical vertebra spinous process). Authors' reasoning behind TENS's success is that since neck proprioceptive inputs play a major role in body segment position and orientation in space and during locomotion [33], possible mechanisms of TENS could involve modification of proprioceptive signalling processes through vibratory stimulation of neck muscles. Apparently, the authors' neck-centric explanation is not based on the SCT that is vestibular and visual system-centric. Instead, it seems that PIT can be used to explain TENS's success. PIT was proposed by Stoffregen and Riccio who postulated that animals experienced sickness when they were incapable, for whatever reason, of maintaining a stable posture. They have suggested that this instability, which occurred prior to the onset of the symptoms of MS, was a necessary prerequisite of this response. Therefore, we speculate that if the neck's ability in posture control is enhanced, then CS will be alleviated.

C. Reliability

1) To what extent CS can be mitigated.

The simulator sickness questionnaire (SSQ) is a commonly-used subjective measure to score the severity of CS [34], and thus can be used to verify the effectiveness of mitigation techniques. An important advantage of the SSQ is that a wide variety of symptoms can be assessed. These symptoms are sub-categorized into three specific symptom clusters: Nausea (N), Oculomotor (O), and Disorientation (D). Nausea includes symptoms of feeling of nausea, stomach awareness, increased salivation and burping; Oculomotor includes eyestrain, difficulty focusing, blurred vision and headache; and Disorientation includes feelings of dizziness and vertigo. The total score of the SSQ is calculated by the weighted sum of the three scores of symptom clusters and is used to describe the overall severity. As shown in Table 1, we found that VR-centric approaches could mitigate all three kinds of symptoms, while the human-centric ones could only alleviate one of the symptom clusters or only the total score. Specifically, we found that d-GVS obtained reduced scores in SSQ total rating and all three SSQ sub-categories. The GCS decreased SSQ total score, but the scores in three subsections were not shown in the paper. However, by personal communication, authors confirmed that GCS was also effective in reducing the three sub-categories' scores. For tDCS, anodal stimulation on TPJ area had a reduced SSQ-D score, while the SSQ-O score was decreased for anodal stimulation on the prefrontal area. There were no statistically significant differences in SSQ total score for both TPJ and prefrontal conditions. Regarding TENS, only the reduced SSQ total score was found to be statistically significant. For i-GVS, one of studies did not find any SSQ-based mitigation in the total score or sub-category scores. However, the mitigation effect could be proven by another subjective assessment — the fast motion sickness questionnaire (FMS) [35]. Unlike the SSQ which was used to score CS severity differences in pre-post electrostimulation, the FMS could rate CS severity quickly during electrostimulation. Thus, FMS has higher time resolution than SSQ. However, FMS requires that participants focus on nausea, general discomfort, and stomach problems only and finally give an overall single score for all these symptoms. Thus, to some extent, reduced FMS can be regarded as reduced SSQ-N score captured during stimulation, indicating that this i-GVS approach relieved N-type symptoms during stimulation. For another i-GVS study, authors used an objective way to claim the mitigation effect (That is, the latency between visual motion onset and perceived vection onset, denoted as T_{vec}). Vection usually occurs after a delay of several seconds following visual motion onset, whereas self-motion in the natural environment is perceived immediately. Authors believed that this latency relates to the sensory mismatch between visual and vestibular signals at motion onset, therefore a reduced T_{vec} indicates mitigated mismatch. However, they did not link shortened T_{vec} to any symptoms. Thus, the concrete mitigation effect remains unknown.

2) Objective evidence on mitigation.

Some studies suggested that the MS symptoms were mediated through the autonomic nervous system (ANS) [2]. The ANS is influenced by its branches including the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) [36]. Heart rate (HR) and heart rate variability (HRV) are two commonly-used measures to evaluate the excitability of ANS. HRV signals are defined as the constant change of the interval between HR and can be easily obtained by analysing a time series of beat-to-beat intervals that are measured by an electrocardiography or derived from a pulse wave signal that is measured using the photoplethysmography waveform. In the frequency domain, the HRV is usually grouped into very low frequency (VLF: 0.003–0.04 Hz), low frequency (LF: 0.04–0.15 Hz), and high frequency (HF: 0.15–0.4 Hz) by means of fast Fourier Transform-based power spectrum density. LF and HF represent SNS and PNS activities respectively. Thus, the LF/HF ratio can be used as the indicator of balance between SNS and PNS activities. As shown in the TENS study, HR and LF/HF ratio increased with the induction of CS, indicating that SNS was elevated while PNS was suppressed during CS. All of these effects of CS on HRV were ameliorated (e.g., decreased HR and LF/HF ratio) with TENS treatment. However, in one of the tDCS studies, the HR did not show any significant difference. This is probably because of some motion artefacts being caused by self-adjustment (e.g., deep breathing, swallowing and retching [37]), which in turn influenced the signal reliability of HR. Thus, regarding motion artefacts, it appears that postural measurement is more robust than physiological data with low signal-to-noise ratio. As reported in the same tDCS study, the centre of pressure (COP) length showed a significant increase after tDCS treatment, which is consistent with the decreased SSQ-D scores. The COP length is the period of time during which the participant is able to stand on the middle of a balance board (e.g., Wii Fit; Nintendo Co. Ltd., Japan) as still as possible with both arms beside the body and feet close together with eyes open.

D. Practical Utility

1) Compensated vestibular responses are not enough.

TABLE I

MITIGATION EFFECT IN DIFFERENT E-CSM CONDITIONS

Comparison \ e-CSM			VR-centric			Human-centric				
			d-GVS		GCS	i-GVS		tDCS		TENS
			[8]	[40]	[12], [21]	[22]	[23]	[29]	[30]	[32]
Study design			within-subject	between-subject	within-subject	Mixed design (between-subject for GVS vs Sham; within-subject for FMS)	within-subject			
Sample size			N=20	N=11 for control; N=10 for treatment	N=48 for 2020 and N=15 for 2014	N=40	N=12	N=20	N=34	N=15
Induction of CS			Rollercoaster in VR-HMD	Flight simulator	Driving in CAVE VR	Neutral game and weightless space station in VR-HMD	Rotations of cubes in CAVE VR	Rollercoaster in VR-HMD	Spatial navigation in VR-HMD	Flight simulator
Verified mitigation effect	**Subjective**	**SSQ-TS**	√	√	√	×	-	×	×	√
		SSQ-N	√	√	-	×	-	×	×	×
		SSQ-O	√	√	-	×	-	×	√	×
		SSQ-D	√	√	-	×	-	√	×	×
		FMS	-	-	-	√	-	-	-	-
	Objective	T_{vec},	-	-	-	-	√	-	-	-
		HR	-	-	-	-	-	×	-	√
		HRV	-	-	-	-	-	-	-	√
		COP	-	-	-	-	-	√	-	-
Real-time mitigation			YES			NO	YES	NO	NO	NO
Aftereffect			NO			Maximum 3 min	NO	At least 15 min	-	At least 30 min

Where, "√" and "×" stand for the statistically significant or insignificant difference between CS treatment session (or group) and control session (or group). The "-" stands for unavailable data. "Sham" stands for the fake GVS for the purpose of comparison. HMD refers to virtual reality head-mounted display. CAVE refers to cave automatic virtual environment, which is a specially designed room in which the walls, ceiling, and/or floor are covered with a screen that can project virtual images or videos.

Vestibular sensory organs are composed of the semi-circular canals and otoliths. The semi-circular canals sense head rotation, whereas otoliths sense linear head acceleration (gravity and translational acceleration) [38]. Since d-GVS and GCS are able to induce head rotation, the semi-circular canals-related mismatch seems able to be compensated well. Actually, the stimulated angular degree has specific range [18], which is still impossible to exactly match with the moving visual surroundings. Furthermore, we did not find any evidence that d-GVS and GCS could induce linear head acceleration. Thus, this is an obvious limitation when d-GVS and GCS are applied to VR scenes that involve linear acceleration, such as rollercoaster diving (gravity acceleration) or car's linear acceleration (translational acceleration).

2) How long does the stimulation take to work?

Since CS causes suffering, the rapid mitigation is a must in real-life applications. Given the compensatory nature of d-GVS and GCS, they are able to mitigate CS with immediate effect, while one of the i-GVS approaches (1.96mA at 40Hz) was also shown to be able to mitigate CS with immediate effect [23]. However, in another i-GVS study (randomized frequency (<100Hz) and current intensity(<1.75mA)), an 18-minute delayed mitigation effect was reported based on FMS every 3 minutes [22]. We did not find any studies that focus on the mitigation assessment during tDCS and TENS, thus their immediate effect remains unknown. However, based on the duration of stimulation, we can surmise that the time to take effect after stimulation started was a maximum of 15 minutes for tDCS [29] and a maximum of 30 minutes for TENS [32]

3) Aftereffect

Aftereffect refers to the time length that the effectiveness can be maintained after stimulation finished. For d-GVS and GCS, the aftereffect is not applicable. Regarding i-GVS, a 3-minute aftereffect was found [22]. Based on the duration of aftereffect assessment, we found that tDCS and TENS have at least a 15- and 30-minute aftereffect, respectively [29],

[32]. Thus, unlike the aforementioned immediate effect, VR users can use tDCS and TENS as a precautionary CS countermeasure rather than a real-time solution. However, it is unclear whether the immediate and precautionary effect is comparable.

4) Practical hurdles in engineering

Although with the development of low-power wireless communication and miniatured electronics, electrostimulation can be designed to be wearable [8], VR-centric approaches require software-coupling between the VR platform and the stimulation device, which may limit the accessibility of VR technology — after all, asking every VR app developer to combine app design and electrostimulation together is not easy.

5) Practical hurdles in user experience.

The possible sensations of slight tingling and itching commonly found with electrostimulation might be not acceptable by everyone [39]. A current intensity of 1 mA has been sufficient to produce tingling [40], let alone the higher ones used here (e.g., 1.96mA for i-GVS, Weech & Troje [23], 2017; 1.5mA for tDCS [29]). More worryingly, these uncomfortable sensations can be worsened once poor contact between skin and electrodes occurs as is likely inevitable in interactive VR. Although conductive gel or saline-soaked electrodes are helpful in improving skin-electrode conductivity, it seems likely that users will be reticent to get their heads or ears wet or sticky if they just want to use VR for fun, impeding adoption of such solutions. More importantly, putting on gel or wet electrodes is not a job that a single person is able to effectively perform.

IV. Conclusion and Future Studies

A. RQ1 to RQ3 (techniques, underpinnings, aetiologies)

The current state-of-the-art e-CSM adopted a variety of techniques to mitigate CS, including d-GVS, i-GVS, GCS, tDCS and TENS. Most of these e-CSM techniques were based on the aetiology of SCT, thus the theoretical underpinnings were either stimulating vestibular sensory organs (such as d-GVS, GCS) to compensate the mismatched visual-vestibular sensory inputs or directly inhibiting them (such as i-GVS) or indirectly inhibiting the related cortical areas (such as tDCS) to make an artificial and temporary dysfunction in vestibular information processing. Only a unique study about TENS seems based on the aetiology of PIT.

B. RQ4 (reliability)

It is hard to conclude which e-CSM technique is the most reliable. Although VR-centric methods achieved better mitigation effect, they were based on pure subjective assessment. Although a few human-centric approaches adopted combined subjective and objective assessments, at-best only few CS symptoms could be mitigated or an overall relief effect demonstrated.

C. RQ5 (application)

Technically, VR-centric solutions are believed to be workable in real-life application. However, our concern is that the acceptance of such technology will be impaired if those (potentially unpleasant) electric current-induced sensations persist.

D. Future Studies.

1) Better Inhibition on Cortical Areas

Inspired by tDCS, future cortical studies can be planned with alternating current (AC) stimulation [41] to see if AC stimulation could achieve better inhibitory effect. This is because the brain neurons have oscillatory nature (e.g., the commonly-known brain wave electroencephalogram), therefore we surmise that the AC stimulation that has an anti-phase with neurons oscillation may indeed follow a better pattern of results than tDCS.

2) Multimodal Objective Measurement

Eye movements and body temperature have been claimed the most reliable objective measures of CS symptoms in comparison to other physiological signals [42]. This is especially pertinent given that consumer VR with built-in eye-tracking functions (e.g., Vive Pro Eye) have become available in the market. Thus, future studies can be planned with multimodal objective signals, particularly carried out during human-centric solutions to investigate the real-time mitigation effect

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