Chapter 6 – MITIGATION METHODS

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6.1 DESIGN MITIGATION METHODS

This section will examine various approaches to mitigate harmful effects of cyber sickness from an application design point of view. For a VR experience to be designed to mitigate possible user's cyber sickness means to devise interaction mechanisms and visual techniques which somehow make the immersed user feel more comfortable in perceiving, moving, and interacting with/within the virtual environment with respect to human own sensory perception system.

6.1.1 Visual Realism

In an era of near photorealistic real-time 3D graphics capability, it might seem obvious to suggest pushing graphics to the highest quality possible – while safeguarding the HMD target frame rate / max latency – in order to make a VR user feel comfortable in a lifelike synthetic representation, and thus hopefully being less prone to sickness. It is intuitive that a high-level of visual realism is positive for raising the sense of presence in a credible operation environment and thus e.g., the effectiveness of the VR training. Nevertheless, some evidence has been found that a high visual realism of the scenes fed to VR users could lead to cybersickness more than the less realistic ones [1], [2], [3]. A first hypothesis for this is that graphically realistic scenes are more perceptually demanding, but another explanation has been proposed: as the visual stimulus becomes more similar to reality, the user is more immersed in the VR and expects vestibular inputs corresponding to the visual stimulation. However, users cannot acquire such vestibular information, so the degree of conflicts as well as VR sickness increases [1], [4], [5].

A mitigation suggestion on this topic is to be ready to downgrade at runtime the rendering quality to graphically simpler representations (e.g., disable effects, advanced lighting, textures, and so on) as discomfort phenomena arise in users in order to check if the excess of visual realism is their cause.

6.1.2 Body Perception / Embodiment

Embodiment, or self-embodiment, is the illusory sensation for a VR user of perceiving his/her own body counterpart in a virtual human body representation present in the virtual environment ("being there") [6]. Beside the natural look of the 3D virtual body representation, an effective own body perception requires that real and virtual bodies have to perfectly match both in time and in the 3D co-registered spaces. A number of parts of the real body (e.g., knees, feet, elbows, pelvis) have thus to be tracked other than the head and hands at a rate according to the HMD scene refresh rate, and the tracking+display system must make these to appear in a credible position to the user with respect to where his/her proprioception makes him/her believe that they are.

Whilst embodiment is clearly an effective comfort-rising strategy for a VR user, it remains unclear its relationship with cybersickness [7]. Nevertheless, implementing it in a VR app could be explored to mitigate the risks of possible disturbance implications related to not recognizing himself/herself in the VE.

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6.1.3 Limiting Visual Flow or Field of View

As counterintuitively as the case of visual realism, a large field of view is not always considered to have a positive effect on human performance in VR. It is a desirable feature when the scene around the user is almost static, and when there’s no, little, or slow movement – either for a linear change of position or due to the rotation of the subject’s point of view such as when he/she looks around. It comes out instead that, when the visual flow becomes substantial, the amount of scene motion perceived by the immersed user in the peripheral parts of the vision can lead to oculomotor disturbance and to cognitive overload.

When is not possible to reduce the visual flow by limiting the linear speed of the user’s movement, and/or limiting the speed of the camera rotation related to user’s head tracking, a trick is dynamically restricting the field of view by a graphic obscuration of the viewport periphery by a factor proportional to the speed magnitude [8].

6.1.4 Visual Acceleration

Linear or angular visually perceived accelerations, which do not correspond to vestibular stimulations, are particularly harmful in immersive VR as these are at the base of the so-called Visually-Induced Motion Sickness. In a VR simulator, these can occur when the user is on board a moving vehicle, and if there’s no motion platform to stimulate his/her vestibular system accordingly, or when the visual and the simulator platform follow each its own rules for rendering their stimuli.

These camera-initiated movements and the corresponding visual accelerations have to be limited as much as possible for a VR application to be less cybersickness-prone. From this point of view, constant velocity is safe instead since the user unconsciously expects no impact on the vestibular system (refer to Section 5.3.5 for additional discussion).

6.1.5 Reducing Unexpected Movements or Showing Visual Leading Indicators

A cause of sickness for VR users is the sudden, unexpected change of direction in vehicle-attached camera movements. One for all, imagine a VR roller coaster simulator: along the way, a user is visually buffeted left-right, up-down, and maybe even physically solicited by a motion platform or other forms of shaking, and his/her disturbance is as high as he/she cannot foresee the next upset source.

Assuming that, in a VR app, unexpected movements, i.e., those not induced by the user, should be reduced to the minimum necessary, making the user mind anticipate upcoming changes of direction and related visual movements, when predictable, mitigates their suddenness and thus contribute to reducing the related discomfort. To this purpose, semi-transparent arrows or dotted trails can be overlaid to the scene as path leading indicators so actually acting as anticipation helpers of the upcoming visual movements.

6.1.6 Dynamic Focus / Dynamic Blurring

Despite the different depths at which objects/parts are laid out in the virtual scene, in a typical Computer Generated Image (CGI) all objects/parts appear to be in focus. The importance of blurring less-important areas of the scene in favor of the user's attention on the more important ones has been underestimated for a long time [9]. However, when designing such a focus strategy the problem arises on what criteria to base the choice of the focus depth range on.

Whilst impossible for the human sight in immersive VR to accommodate on a plane different from the one of the actual display screens, the convergence angle can instead be detected by eye tracking, which modern HMDs are more and more equipped with, thus enabling a dynamic focus strategy. Intersecting converging viewing rays with scene objects, the object/part of the scene the user wants to focus can be located by a heuristic model based on an importance function [9]. Then, by difference between its position in the scene and the camera position, the visualization system can find out the focus distance. Focusing "jumps" have to be managed adaptively in order to not introduce a further source of visually-induced disturbance.

6.1.7 Rest-Frame Cues

In a dynamically changing visual scene reflecting unintended camera movements in pitch and roll, the human proprioception system might be misled, and a VR user may feel disoriented. In such situations, graphics cues that remain almost stable in the foreground, or even fixed in the display viewport, helps the user as trusting references to objectively evaluate motion. The reason why rest-frame cues work for contrasting cybersickness is because the disoriented user can cling to them to trust something which is stably positioned in the scene, and/or to distract him/herself from the visual disorientation.

Among rest-frame cues, foreground cues are graphics representations locked to a certain position in the viewport such as a dashboard, a cockpit, a HUD, reference frames, or even simply a 3D virtual nose [10] halved in two in a stereoscopic pair that has revealed surprisingly effective in mitigating the disorientation in immersive VR [8]. Background rest-frame cues are, instead, representations that remain locked to the 3D scene reference frame and may include the typical panorama far-field elements such as the horizon, clouds, mountains, etc., whose space orientation the user trusts [11]. A third type of reference frame is one attached to the real world, which may be anticipated to have the largest mitigating effect. Which type of cue is most effective remains to be tested.

6.1.8 Viewpoint Control

It has been generally agreed that, for reducing the probability of cybersickness symptoms onset in an immersive VR simulation, the viewpoint must be preferably left in full control of the user. Leaving the user the responsibility for initiating and terminating movement makes him/her able to predict it and to anticipate its upcoming visual feedback.

As proven experimentally [12], teleportation has to be slightly preferred to steering locomotion as a user-controlled navigation technique as it can reduce the symptoms of nausea. For those users becoming disoriented anyway, it may be of help starting teleportation by a fade-out of the scene leaving point and ending it by a fade-in the new scene points so to limit the negative impact on the user of a raw scene change.

6.1.9 Reducing Vection: An Unproven Mitigation Method

Sections 5.1.4 and 5.3.8 reviewed the evidence for vection as a contributor to cybersickness and failed to find it compelling. The current literature does not consistently find vection to be a necessary or a sufficient condition for cybersickness or VIMS to occur, nor does it usually find a strong, positive correlation between vection and VIMS. Therefore, reducing vection is not a recommended countermeasure for cybersickness. This is good news, because it means that, provided the visual stimulus is designed and presented appropriately, the vection illusion can be exploited to quickly and inexpensively foster VR engagement by inducing a feeling of self-motion through the virtual world, when appropriate to the goals of training.

Although limiting vection may not reduce cybersickness, VIMS can be reduced by the following stimulus constraints which are more pertinent to the optical flow stimulus than the self-motion percept:

- **Limiting the acceleration and peak velocity** of ambient visual flow. This may reduce sickness by reducing oculomotor [13] and retinal slip contributions [14], [15]. Generally, slower-moving visual scenes tend to elicit vection quickly without much sickness [16], [17]. Presumably, this is because the ambient visual motion (which signifies self-motion) conflicts less with the vestibular cues, which are failing to signal self-motion.

- **Limiting the field of view** tends to decrease sickness, presumably because there is less visual-vestibular frame-of-reference conflict (e.g., as the visual scene accelerates, it is not as readily interpreted as a visual surround contradicting the lack of acceleration stimulus to the vestibular organs.)[2]
- **Limiting sudden changes in velocity and direction** of the visual flow field. As the field changes direction and velocity more frequently, it is likely to produce more sickness but less vection. Presumably, this is because vection does not have time to build to maximum saturation and compellingness prior to the next flow change, and because the changes offer repeated sensory conflicts to the vestibular system, which is signaling a non-moving or constant velocity body movement status.

In conclusion, while some of the visual stimulus parameters can be manipulated to reduce cybersickness, there is not good evidence that such manipulations reduce sickness via an intervening reduction in vection. Rather, it appears that they do so by reducing conflicts between visual and vestibular signals or expected signals, and possibly via a reduction in oculomotor activity. Conversely, when a moving visual stimulus is perceived as a stationary frame-of-reference by a stationary observer, the observer is presented visual information that they are moving and vestibular information (initially) indicates they are not moving. The interpretation that this stimulus specifies self-motion will contradict the vestibular signal initially (when actual acceleration of the body would be expected but is not occurring), or when a change in the direction or acceleration of the visual flow field occurs. However, if an ambient visual scene is moving very slowly at a constant velocity and in an unchanging direction not indicative of body tilt, then experiencing a vection illusion is a good solution to the visual problem presented and encounters very little conflict from vestibular expectations.

6.1.10 UTSA's GingerVR® Unity Tool Kit

John Quarles, an associate professor in the Department of Computer Science at University of Texas at San Antonio (UTSA), and his Ph.D. student Samuel Ang, implemented a number of visual techniques described in this Chapter and in Chapter 5 plus other techniques from research and collected these in form of Unity toolkit ready to be used for application development, and made available in open-source form [19].

The GingerVR® tool kit includes the following techniques for contrasting cybersickness, or motion sickness, during the use of Virtual Reality applications developed in Unity®:

- **SingleNose** and **AuthenticNose**: create a rest-frame for the user [10] (see Section 6.1.7).
- **DynamicGaussianBlur**: a script which dynamically blurs the user's vision based on their translational speed. The rotational speed of the camera determines the sigma value used in the Gaussian function [20] (see Section 6.1.6).
- **ColorBlur**: a script which dynamically blurs the user's vision based on their translational speed. Portions of the image surpassing the specified color thresholds (i.e., brightness) are not dynamically blurred [21].
- **DynamicFoV**: a script which dynamically reduces the user's Field of View (FoV) based on their translational and angular speed [8] (see Section 6.1.3).
- **DotEffect**: a prefab which suspends virtual orbs around the user which move at twice the user's velocity [22].

[2] Note, however, that vection can still be elicited with a small field of view expanding radially [18]. It may be that whether a visual flow field is considered an ecologically valid frame of reference is more important for vection than whether it has a large field of view.

- **HeadSnapper**: a prefab which detects when the user's head rotation speed passes a certain threshold, at which point their perspective is "snapped" in the direction they were turning. After a brief fade to black transition, the camera's orientation is locked, and then rotated by a specified angle along the y axis. The user's vision then fades from black so that they can see again [12] (see Sections 6.1.4and 6.1.8).
- **VisionLock**: a prefab that allows users to lock what they are seeing on screen with a button press. While the effect is active, the image users see will not change with head movement. This effect is currently limited in that all objects in the scene which you wish to rotate with the user's camera must be children of a single parent object, and because physics interactions in the scene are not rotated while VisionLock is active [23].
- **VirtualCAVE**: an asset that spawns a wireframe cube around the user. This cube follows, and rotates along with the user to simulate a cave automatic virtual environment. To use VirtualCAVE, simply drag the asset onto the user's virtual camera in the scene. The asset will spawn the wireframe cube at runtime. The following settings can then be adjusted through the editor [24].
- **FOVUtility**: a utility that allows to measure the user's Field of View (FoV), as Unity's Camera.fieldOfView does not currently support head mounted displays.

6.2 NEUROPHYSIOLOGY COUNTERMEASURES

Symptoms of motion sickness have been experienced by the unique visual-vestibular perspectives that accompany new forms of transportation; from sea travel to camels, automobiles to airplanes and now spaceships to virtual motion through cyber environments [25], [26]. One of the most effective mitigation strategies is the same as it was in ancient times; adaptation through repeated exposure to the sickness producing stimulus [27]. Therefore, the simplest and time-tested countermeasure for most of those afflicted by cybersickness is a gradual adaptation to the new demands on perception as one gets their 'sea legs' for the new motion. This section will begin with the behavioral mitigation strategies, like adaptation, reducing head movements, controlled breathing, since these are the ones, most often applied by those experiencing symptoms. Following that will be more direct, intrusive interventions that involve neurophysiological methods such as neuronal stimulation or pharmacological countermeasures. Finally, recommendations based on those mitigation strategies that seem to have the most support in the literature for efficacy in symptom reduction will be described in the conclusion and a sequence suggested for their applications.

The mitigation strategies discussed in this section for cybersickness draw heavily from the countermeasures recommended for motion sickness. This approach assumes that cybersickness, like motion sickness, is a disorientation of the visual-vestibular perception pathways induced by unusual perceived motions, only in the case of cybersickness, in a virtual environment, without physical movement [28]. Therefore, the countermeasures for one should apply to the other. This assumption remains to be tested, however, as cybersickness is a relatively new phenomenon compared to the ancient phenomenon of inertia-based motion sickness. One of the conclusions of this discussion must be that more research is needed that directly addresses the effectiveness of these strategies in virtual head mounted displays of the kind that will be encountered by NATO forces in training. As there is no completely effective countermeasure for motion sickness for all situations and individuals, none is expected for cybersickness. This chapter will show that there are methods that can dramatically reduce the incidence of symptoms for most people and most of the time.

It must also be mentioned that some degree of non-sickening stress from unusual motion may be warranted in cyber environments, particularly in training, to add to the immersion and realism. Vection, for example, may be desirable in some cases to foster presence in the simulated environment [29], [30]. Making virtual aircraft flight feel as much as possible like a real aircraft, would add to the virtual training at times. However, certain stimuli may prove too sickening for some trainees. If nausea is elicited in the real environment, being simulated, then some lesser symptoms may be desirable during simulation [31]. It may be that the occasional price of virtual realism in training is the risk of virtually-induced motion sickness.

6.2.1 Behavioral Training

Behavioral countermeasures include those strategies that require movement modification such as reducing head movements or limb movements, even standing [32]. These might be difficult to implement in virtual environments, particularly when training must be as close to reality as possible. The symptoms of motion sickness can be exacerbated by reading while moving or by excessive eating or drinking as well as by anxiety or emotional states [33]. The same is not known in cybersickness and, although likely, needs to be determined. The behavioral mitigation strategies are far more numerous than the neurophysiological strategies and should be considered the first line of defence in the countermeasure hierarchy as they do not require direct physiological intervention and are generally easier to apply. While effective for most people, these may not be the best option for cybersickness in cases where the time commitment for relief to occur is not possible. More short-term strategies such as limiting head movement or changing eye fixation may offer more immediate relief. However, strategies must be chosen carefully to avoid trainees learning strategies which would hinder performance in the real-world setting.

6.2.1.1 Head Movement

There is a strong relationship between head movements and symptoms of cybersickness. As with regular motion sickness caused by whole-body motion, there seems to be a direct relationship between the number of head movements in a virtual environment and the severity of symptoms [34], [35]. Head movements are more consequential in certain directions. For example, tilting the head in a driving simulation in the direction of the lateral forces in a turn can cause more symptoms than head fixation in the opposite direction of a turn [36], [37]. Also, inappropriately timed head movements to virtual displays of movement seems to increase symptom severity [27], [38].

There is general agreement that limitations in the FoV generated by VE equipment create an unnatural delay in movement perception and that the discrepancy can induce cybersickness. This could mean that head motions in VR could exaggerate the delay and create greater symptoms. There is also evidence that exaggerating head movements so that they approximate the enlarged FoV in VE (reducing the discrepancy) can reduce the behavioral and subjective consequences of the delay [39]. This was even more effective if head and hand movements were amplified to roughly compensate for the perceived discrepancies in FoV and hand motion during a tracking task. There would be some training time needed to accomplish the response quickly, but it could easily be accomplished in cyber environments and improve with use if it seems promising. This could prove to be the simplest and most effective short-term mitigation strategy, but specifics of the movement would have to be worked out.

6.2.1.2 Control Over Exposure

The degree of control one has over unusual motions may be another quick short-term strategy for mitigating motion symptoms [40]. The perception of control and predictability of unusual motion appears to reduce motion symptoms [41]. In a different context, exertion of control reduced motion sickness induced by playing video games on a tablet computer [42], [43].

In a yoked control study, two participants experienced nauseogenic rotation and the one controlling the motion and head movements suffered less symptoms than the passive control [44]. This strategy would require the individual drive the virtual vehicle or fly the virtual aircraft to experience control and the anticipation of what movements to expect before it happens. The extent of symptoms would be expected to be lessened, compared to those who cannot predict or control the movements [45], [46].

6.2.1.3 Eye Fixation

One of the most common strategies in controlling symptoms of motion sickness has long been to simply fixate the eyes such that the unusual motion visual cues are not evident [33]. For example, visual fixation on a target moving in relation to the head was less symptomatic than moving targets relative to the scene [47]. Eye fixation may be closely related to the effects of head movement since the vestibulo-ocular reflex is tightly coupled to head movements. A yet unsolved issue concerns the amount of visual-vestibular conflict interacting with eye fixation, implying that eye fixation may be helpful in some but counter effective in other conditions.

6.2.1.4 Diaphragmatic Breathing

Aircrew have often reported that relaxed and controlled breathing alleviated symptoms of motion sickness. One of the original studies of this effect found that controlled, slow, deep breathing induced parasympathetic responses and reduced tachygastria and other symptoms of motion sickness [48]. Similarly, another study compared controlled breathing to a counting task during a 30-minute exposure to whole-body pitch oscillations [49]. Controlled breathing allowed more to finish the 30-minute exposure with less nausea than the counting task. In another task, respiration rates in phase relation to the motion stimulus compared to spontaneous breathing was effective in controlling nausea [50]. The idea of controlled breathing is consistent with the idea of activating parasympathetic activity which is viewed as consistent with a reduction in stress or anxiety during mildly nauseogenic exposure and may partially explain why tranquilizing drugs, such as the phenothiazines (Thorazine, Phenergan) have an effect on motion sickness. These results suggest that stress reduction or relaxation training to counter nauseogenic stimulation could be another simple, quickly implemented short-term strategy for cybersickness.

It has often been reported anecdotally by aircrew that breathing supplemental oxygen reduced their symptoms of air sickness. Subsequent research found that breathing oxygen did not reduce the symptoms of nausea nor influence the recovery time from nausea, compared to normal air [51]. It may be that the reports of supplemental oxygen aiding in symptom reduction was a case of controlled deep breathing.

6.2.1.5 Using Music and Pleasant Odors

Other means that purport to relax an individual to during stressful cyber environments might be to use relaxing music or odors. In an immersive bicycle simulator, there was less susceptibility to unusual motion effects by music rated pleasant compared to music rated stressful or no music conditions [52].

The degree of symptoms was mild in both studies as was the effect. More severe environments were not tested. These strategies would also require externally applied music or odors that might interfere with the ongoing cyber training. Since the rating of pleasantness seemed to be the key to effectiveness of music and odors, it would be likewise difficult to find the more pleasant of these for each individual with symptoms. Evidence exists that other environmental influences can reduce the symptom severity of bicycle cybersickness. Increased airflow was effective in symptom reduction but not seat vibration [53].

6.2.1.6 Acupressure

Several popular devices use acupressure or electrostimulation, typically applied to the wrist, and delivered by vibration or mild shock for the treatment of sea sickness. Most of the literature in reputable journals suggests either no discernible effect or are barely distinguishable from placebo [54], [55]. A few have reported effects, particularly in the P6 meridian, between the two median tendons on the wrist [56]. The evidence does not support these treatments and they could prove distracting in a cyber training environment. In addition, it is not clear how the underlying theory relates to known physiological and neural processes.

6.2.1.7 Motion Habituation

Behavioral countermeasures to motion sickness may be broadly classified into immediate, short-term behavioral modifications, such as those just described and habituation techniques [27]. Habituation offers the surest countermeasure to motion sickness but, by definition, is a long-term approach. On ships and in space, this can occur within a few days [33], [57]. The effectiveness relies on short duration exposure until uncomfortable symptoms begin and then repeating this, after complete recovery, for longer exposure durations. This regimen seems to work in VR as well [58], [59].

Habituation to motion environments may parallel early experiments in optically adapting to distortions in the visual field [60], [61], [62]. It has been well established that wearing prismatic or mirrored goggles (for example continuously for days) elicits a remarkable adaptation in which visually-based motion errors decline continuously and behavior returns to normal [61], [63], [64]. One conclusion from these and other such experiments is that the visual-vestibular and kinesthetic senses are able to quickly recalibrate when actively interacting with a visually disturbed environment so long as the environment remains constant over time [65]. This conclusion has been made for virtual environments as well [66], [67].

There seems to be a strong individual component to this rate of adaptation [67] and the rate seems to be consistent within individuals across different measures of motion sickness [68], [69]. Sex and age don't seem to be a reliable factor in adaptation rate [62] although few studies have examined elderly individuals.

The visual and behavioral adaptation to a distorted environment is remarkable in that it occurs quickly, resetting a lifetime of normal visual experience. Many experiencing the discomfort of cybersickness terminate their experience without slowly trying to adapt to it. The evidence shows that the adaptation is a long-term phenomenon, if established [70], [71], and may strengthen the longer it is continued [72]. There is good evidence of cross adaptation in that exposure to one visual condition, significantly reduced the adaptation rate in another but similar condition [73]. The implications are that a) habituation to nauseogenic stimuli is possible and rapid, although with a strong individual component and b) that habituation may generalize to a similar but not identical environment. With regards to the last point, one could conceivably train repeatedly on a milder version of the virtual stimulus that is causing the nausea and rapidly adapt to a comparable but more difficult stimuli. Research remains to determine the limitations and characteristics of these implications for cybersickness but habituation is, and has always been, the safest, simplest means to overcome the symptoms of distorted motion.

The U.S., Canadian, Dutch and Italian military have developed extensive habituation programs that desensitize motion sickness response in susceptible pilots and sailors with success rates greater than 85% [74], [75], [76], [77], [78]. However, these can take many weeks to complete.

The military has desensitization protocols that prepare people for flight duty who are resistant to drug remedies. Experienced pilots were found to more than halve their symptoms after 5 successive days of nausea induced by G-training [79]. Uncontrolled eye movements during the unusual motions in a centrifuge have been blamed for the nausea. Remarkably, these protective effects lasted over two weeks.

Habituation to a virtual environment, however, seems to be successful at the cost of an increased postural instability. Kennedy and Stanney [80], for example, noted an increased chance for falling (ataxia) after repeated simulator exposures, as did Bos et al. [81] after watching a single 3D movie in a cinema. The latter also observed that, despite a significant decrease of sickness, postural instability lasted for (at least) an hour afterwards. This is consistent with simulator research, which has found lasting balance-related symptoms (and other symptoms) lasting more than an hour after the end of exposure in 25% of pilots [82].

6.2.1.8 Operational Time Limitation/Desensitization

While motion sickness and anxiety are two different phenomena, they share some symptoms in common. Also, sickening situations can elicit anxiety. A more complex behavioral strategy might be considered for cybersickness-like symptoms that are related to stress or anxiety. Users might be aware of their sensitivity to cybersickness and become anxious of disqualification from training or of embarrassing themselves. User also may have gained a classically conditioned anticipatory response to the sickening situation, which includes anxiety and associated anticipatory symptoms at the mere sight or smell of the eliciting device or circumstance. Forms of counter conditioning have been used very successfully as a behavioral treatment for anxieties and stress for over 40 years [83], [84], and, for example, airsickness [77]. These techniques first train the individual in muscle relaxation and regular breathing techniques with pleasant visual imagery [85]. Then they increasingly approximate the anxiety producing stimulus. Over several days of countering less stressful behaviors with stressful stimuli the response of symptoms can be counter conditioned or replaced with relaxation [86], [87], [88].

The U.S. military has successful airsickness mitigation programs involving a variety of motion countermeasures. Depending upon the branch of service, such programs may involve a brief trial of anti-motion sickness medications during the first few flights following sickness, followed (if necessary) by education concerning motion sickness (causes and mitigations), many sessions of adaptation to head tilting during rotation, and other approaches such as biofeedback. The U.S. Navy program has a success rate of ~85% [75]. While the degree of variance accounted for by each of these measures is not known, it is likely that carefully controlled incremental motion adaptation to (Coriolis cross-coupling head tilts in several directions during passive body rotation) comprises a general enough MS desensitization to permit transfer of adaptation to flying. Nevertheless, in cases where aversive conditioning has taken place and the pilot reacts negatively to the site of the aircraft or smell of jet fuel, training to break that negative response is warranted.

A newer form of counter conditioning is Cognitive Behavioral Therapy (CBT). It is distinguished from the traditional forms in that, rather than imagining pleasant visual imagery, other thoughts are used such as thinking about numbers or poetry or distracting one's thoughts from the stressful stimuli to. This success of these counter conditioning treatments in stress reduction implies that they could be successful in mitigating the stress or anticipation of cybersickness which then may reduce these secondary symptoms. While we were not able to find evidence that they have been tried with motion sickness, at least one study provided the evidence and means to do the studies [89].

These techniques can help in cases where secondary symptoms have arisen due to anxiety or aversive conditioning, but they are time consuming, and they require a level of concentration which renders them difficult to apply in a high-tempo operational situation where sickness has already arisen. In some cases, the fact that a considerable amount of time is needed to acclimatize the user slowly could be an asset as more time for habituation would also occur, combining strategies.

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6.2.1.9 Individual Information Flow Adaptation

Symptoms of motion sickness can be reduced in a projection-based virtual environment by using Earth-referenced rest frames [90]. These rest frames are suggested to produce the effect by allowing the user to maintain some reference, some perceptual contact with the real world and to lose the sense of immersion. Keeping fixed visual outside references, for example, in a projected or HMD cyber experience reduced symptoms during strong rotational motions compared to no references [91]. Consistent with the idea that simultaneous perception of normal, real-world frames of reference during perception of the virtual environment reduces the experience of motion symptoms is the HoloLens. In a study of motion sickness symptoms, when users could see both the cyber environment and the real environment via a HoloLens and only negligible symptoms occurred [92].

Healthy users (but not vestibularly-impaired individuals) experienced less motion sickness in visually provocative environments when an artificial horizon was projected to one eye that was aligned with the head and body position [93]. One eye perceives a real world and the other the virtual world. However, Feenstra et al. [94] found a reduction by a factor of two when projecting an artificial extended horizon that cued 6 DoF of motion). This result increased to a factor of four when adding an anticipatory motion trajectory. These studies suggest that veridical (real-world) sensory cues may reduce symptoms. Maintaining information about the horizon may offer some resistance to symptoms in individuals with a functioning vestibular system.

Manipulating either the amplitude or frequency of visual oscillations, and holding the other variable constant, showed that amplitude changes produced more symptoms than the frequency [95].

For naïve gamers, a study found that a thorough narrative about what they were going to experience in the game reduced their nausea, eye strain and disorientation compared to a simpler narrative [96]. This effect was not found in experienced game players. The authors attributed the effect to knowing what to expect, which reduced inappropriate head and eye movements, hence reducing sickness, but of course, experienced players should already be more adapted to the situation, so perhaps they had less room for improvement.

6.2.1.10 Conclusions

The effectiveness of behavioral mitigation strategies in the short term for immediate relief seems related to the appropriate voluntary control of head and/or eye movements in the cyber environment. The more the individual is in control over the unusual motion or the more predictable the motion is, seems to be help reduce symptoms. If there is time to train, habituation and desensitization techniques seem to work well and last for a while. It may be useful to develop increasingly nauseogenic stimuli for a training device to acclimate the users who experience cybersickness. Repeated exposure to the stimuli, stopping the simulation before they symptoms become too great and repeating the exposure to extend that stopping point may be a useful training strategy. Knowledge of what to expect may play a role in helping to control inappropriate and symptom enhancing visual and spatial misperceptions that could exaggerate the symptoms. An important adjunct strategy, perhaps combined with another mitigation strategy such as adaptation, would be to relax. The use of relaxation techniques in the presence of stressful stimuli, through deep, controlled breathing or more formal relaxation training, seems promising in reducing symptoms.

6.2.2 Neurophysiological Intervention

Most people will experience cybersickness to varying degrees in a virtual environment. The preceding section described effective behavioral strategies that would require the user perform or modify normal reactions to unusual motion stimuli to alleviate the symptoms. The current section will describe neurophysiological mitigation strategies that imply a quick but invasive intervention that typically requires monitoring the user for side effects. They will also work for most individuals but should only be tried when behavioral mitigation training has not worked.

6.2.2.1 Nerve Stimulation – Haptic/Galvanic/Magnetic

Transcranial Direct Current (TDCS) and Galvanic Vestibular Stimulation (GVS) have been reported to be successful in reducing cybersickness symptoms, presumably through adding ‘noise’ to overwhelm or mask ‘confused’ vestibular signals (Section 6.4.2) [97], similar to the beneficial effect of mechanical vibration added to the head [98]. Others have found that mechanical vibration to the head can also elicit symptoms [99]. Since galvanic and vibrational stimuli can either reduce or exacerbate motion sickness, it is important to design and implement these countermeasures carefully.

While lower symptom ratings are reported during stimulation, these effects typically only last for a few minutes after exposure before symptoms return. Although there are several devices that send electrical or mechanical pressure transcranially, purportedly from the one vestibular organ to the other through the head, doubtless other CNS circuits are also affected. These methods produce noticeable side effects on behavior such as twitching or stumbling which only lasts for the duration of the stimulation but can disrupt the immersive experience as well as normal behavior such as walking. Similar results were found using bone conduction of mechanical stimulation to presumably interfere with 'incorrect' vestibular signals and the effect could be enhanced if the projected image was angularly accelerated [98], [100]. It has been shown by others that bone conduction and presumably electromotive or galvanic stimulation, causes linear acceleration perceptions from the otolith organs [101]. The disadvantages of these stimulation techniques, in addition to the extra vestibular stimulation effects, arise from the need for a headset to go under the cyber equipment and that some may become uncomfortable with the invasive stimulation methods.

6.2.2.2 Nerve Stimulation – Information Masking

It may not be necessary to use transcranial stimulation to alleviate cybersickness. The use of tactile stimulation to resolve spatial disorientation, particularly in flight, has been known for some time using vibrotactile belts, seats, or vests [102]. Tactile stabilization of posture has been found from light fingertip vibrations [103]. Blindfolded individuals were shown to reduce postural sway by as much as 50% using fingertip stimulation. In addition, persons who had lost labyrinthine function were shown to stand indefinitely with eyes closed after the tactile stimulation ceased [104].

The effect on postural stabilization from tactile stimulation occurs within a 100 msec, more rapidly than visual stabilization methods [105]. Tactile stimuli have been used to mitigate spatial disorientation [106] but the effect on cybersickness reduction has not been the focus of these studies (e.g., Ref. [107]). Light tactile stimulators could be placed on various parts of the body to indicate movement and direction and this added cue might help to overcome the disorientation of virtual motion and hence, cybersickness.

For vertigo that is hard to treat, a device called a Meniett pulse generator was developed to apply pressure to the middle ear and, presumably, to lessen fluid build-up and produce the effect. Treatment involves application 3 – 5 times a day for 5 minutes at a time. This therapy has shown relief of vertigo, tinnitus, and aural pressure in some studies, but not in others. Its long-term effectiveness hasn't been determined yet.

6.2.2.3 Pharmaceutical Intervention

Pharmaceuticals[3] are used to relieve cybersickness symptoms that are persistent and severe. The importance of anti-nausea and anti-emetic drugs cannot be overstated in situations where a mask could be clogged such as post operatively or during aircraft maneuvers.

A variety of compounds have been used over the last 30 years to alleviate motion sickness in nauseogenic environments [111]. The majority of these consist of anti-muscarinic drugs, such as scopolamine (hyoscine) typically delivered as a patch, and antihistamines such as Bonine (meclizine), Dramamine (dimenhydrinate), or Phenergan (promethazine). The antihistamines are more familiar as they are non-prescription medications but of little clinical significance [112], [113]. Scopolamine, especially when combined with d-amphetamine, appears to be better at preventing motion sickness than any of the antihistamines [112], [114]. However, no known medication will entirely eliminate sickness in severe situations, and there are important operational military considerations surrounding the use of transdermal scopolamine [115]. In addition to its antihistamine and anticholinergic functions, promethazine, a phenothiazine, also acts as a Dopamine (D2) receptor antagonist [116]. The additional effects of promethazine beyond the H1 receptor site could explain its superiority over other Histamine (H1) antagonists. NASA uses scopolamine/d-amphetamine combination

[3] Potential nutraceuticals (e.g., ginger) and alternative medicine interventions (e.g., acupuncture/pressure) often come up when pharmaceuticals are discussed. The evidence for these countermeasures is mixed [108], [109], [110].

and Phenergan for difficult cases of space motion sickness. These drugs work well but have unwanted sedative side effects. Relatively few studies have looked at operationally relevant abilities under controlled circumstances, but one study involving simulated shooting did not detect functionally relevant decrements under a variety of anti-motion sickness drug conditions [115].

Proponents of ginger root extract, as a natural anti-nausea medication, have been around for centuries. It was reported to be used by the Chinese as long ago as 400 BCE as a medicinal for many purposes, including seasickness [98]. The effects of ginger on motion sickness have been well tested and are equivocal at best [108], [109]. Like many compounds with little clinical evidence of efficacy, ginger has remained popular as a recommendation because of a 'false positive' effect; if, after taking it and one doesn't get seasick, it is easy to attribute it to ginger when it could just as well have been that sea conditions didn't produce seasickness, no matter what was taken. The user then becomes an advocate of ginger [117], [118], [119], [120], [121], [122].

The disadvantages of pharmaceuticals to mitigate motion sickness are primarily their sedative actions, amnestic properties or, as in the case of the antihistamines, their clinical reliability. However, when sufficient time to habituate to the cyber environment is not possible then pharmaceutical intervention might be recommended.

Pharmaceuticals are one of the most available, simple, and effective ways to reduce cybersickness, provided they are initiated well ahead of predicted exposure. A wide variety of compounds have been used over the last 30 years as a prophylaxis to alleviate motion sickness in nauseogenic environments [111]. The majority of these are the anti-muscarinic drugs like scopolamine (hyoscine) typically delivered as a patch, and the antihistamines such as meclizine, dimenhydrinate, or promethazine. The antihistamines are more familiar as many are non-prescription medications.

6.2.2.4 Placebo Effect

Researchers go to great lengths to compare medication effects in double-blind, placebo-controlled studies. In a well-designed study examining specifically for placebo effects, ginger was compared to placebo during conditions that used levels of verbal expectations [123]. The study found no ginger effects nor expectation (placebo) effects, but changes in symptoms were found based on interaction with the sex of the experimenters.

In another study, participants were told that a pill would either increase (nocebo) or decrease (placebo) symptoms [124]. Those given the nocebo had fewer symptoms than placebo, even though it was the same pill in both cases. In a subsequent study, males were told a pill would increase symptoms (nocebo) and they showed lowered tolerance for rotational experience but no effect on symptom ratings [125]. The same group found nocebo responses in a rotational chair paradigm [126]. There do not seem to be strong placebo effects in motion sickness research but these authors caution about carefully controlling interactions and making use of double-blind techniques.

6.2.2.5 Conclusions

The most effective anti-nausea drugs, currently in use by the military are scopolamine and Phenergan. It is recommended that if pharmaceuticals are being considered for an individual, to prolong the exposure time due to a reduction in symptoms, that these be ground tested first on the individual. Ground testing should be done under medical supervision and ensures that the individual will not have a reaction during training. Typically, 24 hours should pass before the drug could be considered safe to use on the individual. Additionally, it seems that the behavioral strategies should be exhausted first before the more obtrusive medical strategies are attempted.

6.3 VR HORIZON SCANNING – PROTOTYPES, PRE-COMMERCIAL PRODUCTS, AND PROMISING TECHNOLOGIES FOR CONTRASTING CYBERSICKNESS

6.3.1 Otolith Labs Anti-Motion Sickness Integratable Technology

Following on a first paper showing a mitigating effect of head vibration on motion sickness [127], OtoTech® commercialized a head-worn, strap-on, bone-conducting transducer that uses white noise vibrations to provide consistent, noninformative stimuli to the vestibular system. These vibrations prevent the spatial discordance, which is the root cause of motion sickness, resulting in a dramatic reduction of VR sickness in users. Samuel Owen developed OtoTech® through his company Otolith Labs, Owen said they have observed no other effects of the gadget other than your brain being more comfortable with simulated movement [128]. This technology is currently going through the stages of research approval through the U.S. Food and Drug Administration (FDA), if approved, this technology could have the potential of reducing Virtual Reality (VR) sickness in training simulators for various DoD partners. The prime company that has subcontracted Otolith Labs is VR motion, this company has claimed to have various successes in reducing VR sickness. In fact, CEO Keith Maher told reporters that they have historically seen a 20 – 30 % sickness level among trainees [128], which was captured during their research efforts. It will be interesting to see whether this newly constructed device will in fact reduce VR sickness in during controlled experimentation by third parties.

6.3.1.1 Potentially Related Research Study

Queens University in Canada conducted a research study that utilized Bone-Conducted Vibrations (BCV) to help reduce the levels VR sickness. The method they used involves applying noisy stimulation to the vestibular system using Bone-Conducted Vibration (BCV) that is applied at the mastoid processes [129]. This relevant study reflects a similar approach to that of the strap-on device that Otolith Labs has developed, granted OtoTech® is focused on white noise vibrations, Weech et al.'s study [129], on the other hand, focuses on bone-conducted vibrations which may or may not be correlated. Experiments conducted in the study focused on aerial navigation using oculus plugin in Unity 3D and low-cost infrared hand-tracking camera Leap Motion Controller, Version 3.0.0, [129] while the other utilized a large projector and gaming controller. Essentially, the researchers generated a path for participants to navigate by positioning 30 spherical targets in the environment [129]. Students who participated in both experiments found that BCV did in fact help reduce the levels of VR sickness. In fact, the study showed in both Experiments 1 and 2 that participants exhibited less simulator sickness in the condition where vibration was coupled with angular accelerations of the camera compared with control (fewer than half experienced SSQ scores of 20 or above) [129]. However, some of the VR sickness susceptibility occurred during experiment 2 when the hand-tracking camera connectivity was lost. Many times, if the hand tracking did not work students would not be able to maneuver the aircraft. Furthermore, there were a number of participants that reported 'fatigue' and 'general discomfort' at least once 85% and 72%, respectively [129]. This may have also added to some increased level of VR sickness. These are various factors that may need to be analyzed when defence members are conducting potential experiments in the future as it relates to BCV.

6.3.2 NVidia® Lightweight VR Gaze Tracking System Using LED Sensors

NVidia has constructed a VR eye-tracking system using LED sensors. Although this prototype is going to be very large and costly, it may help reduce VR sickness for potential users due to increased eye-tracking capabilities. This prototype has the ability to both emit and sense light – to simplify the process of determining the eye's position relative to a display [130]. This approach has been used before, but NVidia's approach may be beneficial as LEDs also are used for color-selective sensing from the same location [130]. Furthermore, LED lights surrounding the eyes emit a range of light rays within the infrared spectrum. LEDs also consume little power and rely on comparatively simple controller hardware and software, they cut overall latency, reduce the number of cameras needed by the headset, and remove the need for an extra image processing block within the headset's pipeline [130]. This prototype is still in the research stages; however, it may improve eye-tracking capabilities and reduce VR sickness for various consumers. Defence readers should definitely keep an eye out for this this new technology that NVidia is experimenting on.

6.3.3 PlayStation® VR Motion Sickness Technology

PlayStation® constructed an experimental evolution of its VR headset that has the capability to monitor VR sickness susceptibility in a user and advise him/her on when to remove the headset before the insurgence of severe cybersickness consequences. The new PlayStation VR® tech would use a variety of biometric, moisture, and orientation sensors, as well as advanced eye-tracking cameras, to detect when a player is about to enter in pre-sickness state. The devices sensor configuration consists of various warnings features to help inform players of potential VR sickness risks. Users will receive a visual/audible warning and/or some of the functions of the head mounted display may turn off [131] if it senses that the user is at risk of VR sickness. Granted this does not help prevent VR sickness, but rather informs players to pause and take a break from VR gaming prior to potentially getting sick. One key factor to acknowledge is that this device is a patented product constructed by Sony [132]; therefore, a potential research collaboration with Sony may be a potential advantage for defence partners. Although the concept of incorporating a VR monitoring system for military training simulators doesn't necessarily reduce VR sickness, it still could be of value in VR sickness realm.

6.3.4 Half Dome® 2 and 3 Varifocal VR Headset Prototypes

Facebook® scientists have developed a prototype headset known as the Half Dome 2®, which is a small headset with a 140° field of view and an adept Varifocal system, which has been shown to provide a clearer video quality within a VR application. The Half Dome 2® has a varifocal system that consists of a new type of liquid crystal lens made from a thin, alternating stack of two flat optical elements: Polarization-Dependent Lenses (PDLs) and switchable half-wave plates [133]. With a narrow stacked PDL structure, this allows the user to easily adjust the headset focus with very limited blur or visual limitations. Essentially, with the six liquid crystal lenses, the system can cycle through 64 focal plans (the number doubles with each additional lens) for smooth transitions between focal depths [133]. This allows players to see the finer details of certain objects within the VR setting, thus having the potential of reducing sickness within virtual reality. Furthermore, Facebook is already beginning designs for the Half Dome 3®, which is planned to not only be smaller than its predecessors, the Half Dome 1® and 2®, but will also eliminate more noise and vibrations. Defence users may benefit from Facebook Half Dome 2® and 3® prototypes, as they continue to improve the visual capabilities in VR via their varifocal system; thus, potentially helping reduce VR sickness in training simulators in the near future. As with public users, defence users should be fully apprised on any data being gathered by corporations, and confident in the uses of such data.

6.3.5 WalkingVibe®

Scientists from the Taiwan University created an experiment noted as the WalkingVibe® [134] to test whether active visual, sound, and tactile cues would help reduce levels of VR sickness in their participants. Essentially, this was a 240-person study to compare 4 vibrotactile designs with 3 audio-visual conditions and a tactile condition with PhantomLegs®, the authors previous work [7]. Participants were placed in a seated chair, with an upgraded HTC Vive Pro Eye® and told to walk through the various virtual scenarios. The study showed timing and location for tactile feedback had significant effects on VR sickness and realism [134]. Furthermore, the use of synchronization by means of visual, audio, and tactile vibrations has been shown to improve participants experience in the virtual realm, as represented in the study. In fact the study results showed that the tactile conditions (i.e., 2-sided tapping (synchronized), 2-sided vibration (synchronized and random)) significantly reduced participants' VR sickness – compared with two visual-only (with and without head-bobbing), audio, and backside vibration (synchronized) conditions [134]. The utilization of synchronized walking vibrations and audio were inherently better tools that helped reduce VR sickness and improved overall realism and experience within the virtual environments. The WalkingVibe® prototype still requires much work as scientists continue to improve the audio and vibration testing at 150 Hz for future studies. A rudimentary spatiotemporal cue such as this should not be confused with a full tactile orientation suit or vest. Defence partners may still find that there is a benefit to embedding audio, visual and a vibrotactile synchronization systems within a headset to potentially help reduce VR sickness for their military simulators, however this would eventually have to go through a validation process.

6.3.6 The HP Reverb G2® Omnicept® and Other Sensors-Integrating HMDs

Built upon the basis of the visually-excellent HP Reverb G2®, the Omnicept® Edition [135] – which is expected to appear on the market in Spring 2021 – add a number of sensors for monitoring the wellbeing of the immersed user such as eye tracking and pupillometry (by the Tobii sensor, which actually measures muscle movement, gaze, and pupil size), heart rate, and a face camera. An Omnicept® platform then collects and analyzes all these data in real-time with machine learning algorithms, delivering high-level insights. Training applications could take advantage of measuring a user's cognitive load (determining how much "brain power" a user is exerting on the task at hand) thus giving a better understanding of the trainee's performance and ability to make decisions and/or delivering experiences that better prepare teams to deal with high-risk situations such as dismounted soldiers. Furthermore, with these integrated sensors, VR applications can track user engagement and assess user responses at any moment, and, with the face camera, avatars can display authentic facial expressions. From a cybersickness reduction point of view, Omnicept® sensor data can be monitored to analyze and promptly detect the insurgence of VR-related illness and has the advantage of a highly integration of body sensors within a state-of-art head mounted display unit in a commercial grade product.

Maybe the ultimate mode of capturing a user mental state for measuring a user's cognitive load is collecting data through a real BCI-BMI, whose integration into next generations VR HMDs is expected in one to three years (research-oriented products from LooxidVR address both PC VR headsets – in form of an add-on – and mobile-powered VR headsets combining eye-tracking and dry EEG electrodes for capturing brainwaves). Valve, OpenBCI and Tobii announced the launch of a VR Brain-Computer Interface named 'Galea®' in early 2022, for experimenting with neural interfaces on the basis of the Valve Index PC HMD®, and, to hear to Valve CEO, "to solve VR motion sickness and to increase immersion".

6.3.7 Case Study: Virtual Reality Pilot Training Simulator

The U.S. Air Force Research Laboratory's (AFRL) Gaming Research Integration for Learning Lab® (GRILL®) has been a key proponent and developer of game-based training utilizing commercial game engines and virtual and augmented reality approaches to provide dynamic and effective instructional solutions to Warfighter. The GRILL® team has extensive experience in developing custom training solutions with advanced technologies in multiple application arenas, such as undergraduate and helicopter pilot training. Both training simulator utilize Prepar3D® Professional Plus V4 Developer License, HTC Vive Pro Eye®, GeForce 2080 Ti®, gaming chair, stick/throttle, and rudder pedals for training purposes. GRILL® engineers have received feedback from various pilots noting that they have experience little to no VR sickness in our simulators. Some of the key features that may limit VR sickness are but not limited to, the simulators realistic aircraft and landscape visuals, its stationary positioning and the well-designed gaming chair and software/hardware add-ons. This highlights that a low-cost training simulator could be used to help reduce VR sickness as well as effectively train pilots during training scenarios, as observed by the engineers.

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