ORIGINAL ARTICLE

A review of cybersickness in head-mounted displays: raising attention to individual susceptibility

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Abstract

Cybersickness still poses a significant challenge to the widespread usage of virtual reality, leading to different levels of discomfort and potentially breaking the immersive experience. Researchers have attempted to discover the possible fundamental causes of cybersickness for years. Despite the longstanding interest in the research field, inconsistent results have been drawn on the contributing factors and solutions to combating cybersickness. Moreover, little attention has been paid to individual susceptibility. A consolidated explanation remains under development, requiring more empirical studies with robust and reproducible methodologies. This review presents an integrated survey connecting the findings from previous review papers and the state of the art involving empirical studies and participants. A literature review is then presented, focusing on the practical studies of different contributing factors, the pros and cons of measurements, profiles of cybersickness, and solutions to reduce this phenomenon. Our findings suggest a lack of considerations regarding user susceptibility and gender balance in between groups studies. In addition, incongruities among empirical findings raised concerns. We conclude by suggesting points of insights for future empirical investigations.

Keywords Cybersickness · Virtual reality · Literature review · Individual susceptibility

1 Introduction

The immersive capabilities of virtual reality (VR) have provided a powerful platform allowing users to engage and actively interact with virtual 3D content unlike any other form of media. Given these capabilities, it is no wonder that several research fields have found interest in leveraging VR beyond entertainment, such as education, rehabilitation, and controlled psychological therapy. Unfortunately, despite the constant advancements in virtual headset technology, cybersickness continues to be a problem in VR, impeding its commercial expansion and wider adoption due to the uncomfortable side-effects (Gavgani et al. 2017). Despite a highly active research topic, the problem of cybersickness continues to be an issue and is far from being solved (Yildirim 2019; Szpak et al. 2019; Nalivaiko et al. 2015).

In previous review papers, cybersickness was studied through various perspectives, where for example, LaViola (2000) explored a series of contributing factors and methodologies alleviating cybersickness side-effects. More recently, in 2016, Rebenitsch and Owen (2016) surveyed the literature considering two aspects: cybersickness measures (e.g., questionnaires), postural instability, and physiological states; and different types of displays, rendering methods, and application design. Contradicting LaViola, Rebenitsch and Owen (2016) reported that cybersickness did not decrease with technological advancements and presented a list of alternative factors contributing to the phenomenon. Finally, Saredakis et al. offered a meta-analysis on the influence of virtual content and specific cybersickness side-effects (Saredakis et al. 2020) and concluded that the virtual content itself could be a significant factor contributing to cybersickness. This suggests that cybersickness is not solely based on the quality of the technology itself (e.g., field of view and graphic fidelity) but also how this content is presented to the individual. Hence, generalizing design guidelines for any virtual environment is impossible given the series of conflicting results across prior studies, even when focusing on the same strategy to alleviate cybersickness. What is more,

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the most recent reviews explicitly focused on individual susceptibility (MacArthur et al. 2021; Howard and Van Zandt 2021; Stanney et al. 2020). For instance, Macarthur et al. raised the attention to include and report women's experiences to understand the gender effects better (MacArthur et al. 2021). Furthermore, Howard and Zandt's study (Howard and Van Zandt 2021) indicated a series of human factors that are significantly associated with cybersickness (such as motion sickness susceptibility, gender, real-world VR experience, or related experience). Meanwhile, they obtained uneven results across various individual differences. Finally, Stanney et al. provided an essential synthesis of past and present critical studies, a future agenda towards eliminating cybersickness was proposed in their review (Stanney et al. 2020). The agenda highlights the high importance of the need to first address the following issues in future development agenda: (1) identifying contributing factors and their weightings; (2) establishing guidelines for content design to mitigate cybersickness; (3) investigating the relationship between sensory cues and individual susceptibility; (4) defining strategies to help users better adapt XR systems;

(5) exploring the relationship between individual sensitivity and postural instability; (6) understanding the sensorimotor processing characteristics that can benefit cybersickness reduction; (7) last but not least, the tuning effect of tasks parameters on cybersickness and presence (Stanney et al. 2020).

Thus, the issue is far from eradicated due to the series of conflicting reports on the causality and the underlying physiological mechanisms that occur during cybersickness events (Howard and Van Zandt 2021). Furthermore, the previous review papers also suggest that a general solution for this problem, i.e., "a one size fits all" solution, may be challenging to achieve due to the different susceptibilities of each individual to one (or more) factors that lead to cybersickness. The reasoning is that in previous work, individual susceptibility tended to invalidate cybersickness mitigation solutions when tested on different groups of individuals (Martirosov and Kopecek 2017). Therefore, this review paper attempts to compile and further understand the different aspects that can lead to cybersickness by exploring each potential factor influencing an individual (Fig. 1).
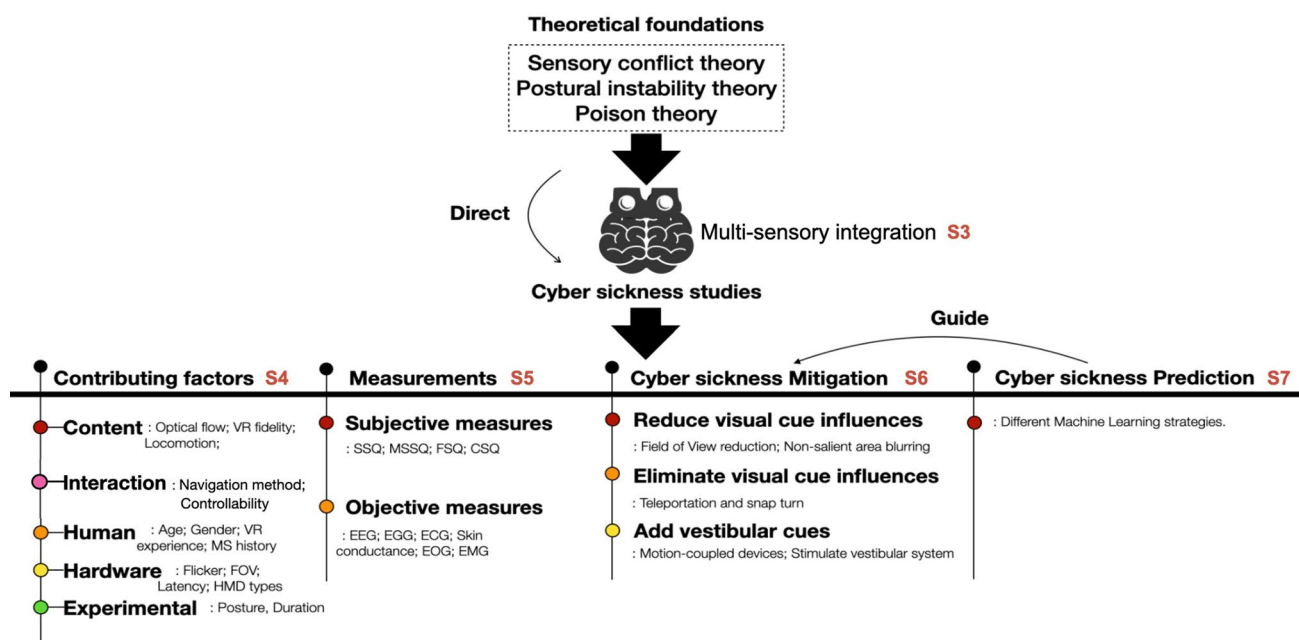

Fig. 1 Integrated model of cybersickness with three proposed theoretical foundations (Sensory conflict theory (Oman 1989) as the oldest and most accepted. Postural instability theory (Riccio and Stoffregen 1991) is becoming a popular alternative against sensory conflict theory, while Poison theory (Treisman 1977) is the least valid.). The theoretical foundation directs the current studies of cybersickness. The first is the contributing factors, and we classify these factors into five categories: content, human, hardware, experimental and interaction. Measurement of cybersickness is essential in empirical studies, and subjective measures are primarily used. Moreover, physiological measures have also become popular recently. Cybersickness mitigation is also a well-studied topic. Finally, the prediction of cybersickness provides a better balanced solution to generalize the mitigation methods. The associated sections are labeled in Red (e.g., the S3 represents Sect. 3)

2 Survey methods

By following the PRISMA guidelines (Moher et al. 2009), the authors surveyed an extensive list of published papers that occurred over the past six years (Fig. 2). A rigorous search was performed to obtain a comprehensive overview of the current state of the art concerning cybersickness using IEEE, ACM digital library; Springer; Web of Science, and Google scholar. One difficulty in finding related sources was the inconsistent use of terms reporting such adverse effects, which resulted in a wide range of false positives that contained similar but unwanted contents (e.g., papers that focus mainly on motion sickness like car sick). To rule out the massive studies on traditional motion sickness, the search queries include the following combinations: "Cybersickness AND Virtual Reality," "VR sickness AND virtual reality," and "Cybersickness OR VR sickness OR Simulated Sickness AND Virtual reality." We reviewed a corpus of papers selected through a PRISMA (Moher et al. 2009) within the time range of January 01, 2015, to August 31, 2021. A final set of 165 studies was included in this literature review. By screening the titles and abstracts, the papers containing keywords like cybersickness or VR sickness or visually induced motion sickness or motion sickness in Virtual Reality were identified for eligibility. The decisions for exclusion were made via criteria defined in Table 1. Finally, selected papers were further grouped by their primary subject. Some papers studied multiple aspects of VR experience like sense of presence, emotions, and other gaming experiences. We only report results related to cybersickness. The results of these inquiries are summarized in tables in the following sections.

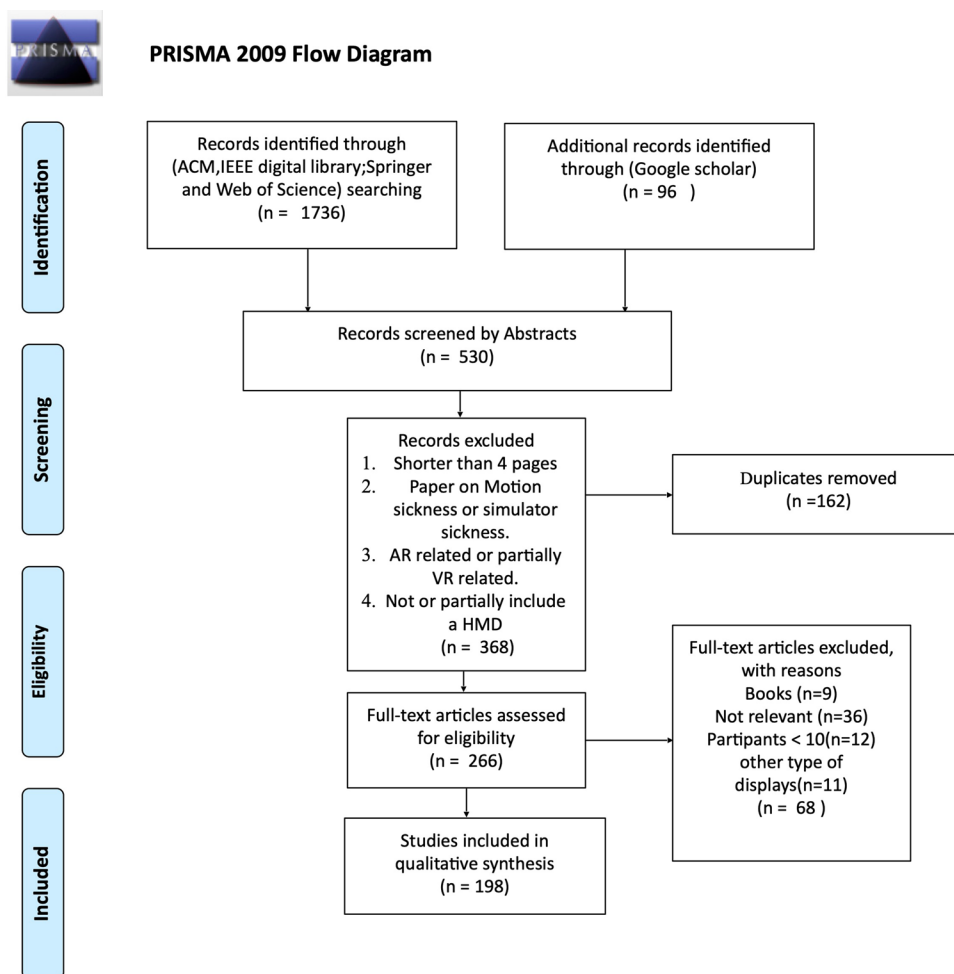## 3 Neural mechanisms underlying individual susceptibility

Self-motion perception involves a multisensory convergence of sources from visual, vestibular, somatosensory, and proprioceptive cues (Greenlee et al. 2016). The vestibular system generally delivers information on angular rotation and linear acceleration of the head in space. Visual signals include optic flow on the retina. Meanwhile, proprioceptive and somatosensory signals together contribute to sense body parts' relative positions and movements in 3D space (Gallagher and Ferrè 2018). Understanding the multisensory integration process for self-motion perception is essential in shaping perceptual experiences. The underlying neural mechanism behind the integration is to reweight sources to reduce perceptual uncertainty. Practically, the sensory cues are weighted by their reliability. Which one is reliable and thus more dominant depends on particular situations (Gallagher and Ferrè 2018). There are indications of such overweighting process of the vestibular signals during integration in cybersickness. When sensory conflicts are detected, the brain considers the vestibular cues more reliable and increases the weight, generating an "optimal" combination of signals and potentially leading to cybersickness. Based on these findings, Gallagher and Ferrè suggest down-weighting the vestibular inputs and up-weighting the visual inputs to reduce cybersickness (e.g., through artificial vestibular stimulation) (Gallagher and Ferrè 2018).

Observation of such reweighting process during cybersickness is a difficult task. Hence, what is not yet clear is the exact neural mechanisms underlying individual susceptibility (Harada et al. 2021). Recently, studies on motion sickness susceptibility reveal the facts that individuals with greater bilateral asymmetry in otolith sensitivity are more susceptible to motion sickness (Sakai et al. 2021). Moreover,

Table 1 Selection criteria

Inclusion criteria	Exclusion criteria
Original, peer-reviewed full papers on cybersickness published from 2015.01.01 to 2021.08.31 in English	Papers on human study with a low sample size (Total participants < 10)
Papers examining factors that have an impact on cybersickness should be evaluated with human participants with provided empirical evidence of an effect. The experiment should involve using VR Head-Mounted Display (HMD)	Papers focusing solely on "motion sickness" such as: car, boat and airplane sickness; and simulated sickness: flight and driving simulations.
Papers on measurements, either subjective or objective or combined, should have a focus on verifying subjective or objective indicators of cybersickness.	Studies on cybersickness without or partially using Head-Mounted Display (HMD).
Papers on combating cybersickness should have precise descriptions of the innovative method and evaluation of its effectiveness.	Studies reporting more than one kind of VR experiences, resulting in a minor discussion on cybersickness.
Full paper submissions (i.e., papers with more than 4 pages, excluding references)	Augmented reality related or non-fully immersive displays related experimental studies.
Papers on experimental human studies with healthy subjects.	Books or book-related chapters.

Fig. 2 Total number of papers identified by database and numbers of papers shortlisted as relevant for review

PRISMA 2009 Flow Diagram

Identification

Records identified through (ACM,IEEE digital library;Springer and Web of Science) searching (n = 1736)

Additional records identified through (Google scholar) (n = 96)

Screening

Records screened by Abstracts (n = 530)

Records excluded
1. Shorter than 4 pages
2. Paper on Motion sickness or simulator sickness.
3. AR related or partially VR related.
4. Not or partially include a HMD
(n = 368)

Duplicates removed (n =162)

Eligibility

Full-text articles assessed for eligibility (n = 266)

Full-text articles excluded, with reasons
Books (n=9)
Not relevant (n=36)
Partipants < 10(n=12)
other type of displays(n=11)
(n = 68)

Included

Studies included in qualitative synthesis (n = 198)

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097*

For more information, visit www.prisma-statement.org.

the study also indicates that the individual variability in the reweighting process could determine individual susceptibility; more detailed research, however, is needed to prove this assumption (Gallagher and Ferrè 2018).

3.1 Interesting brain areas

There is no summary of interesting brain areas established for observation of cybersickness occurrence until now. Based on the development of cybersickness, ideally, notable brain areas could reflect the potential visual-vestibular interaction along with the interplay between brain and visceral efferent and afferent circuits that leads to processes of typical symptoms such as dizziness, nausea and vomiting (Keshavarz and Golding 2022). In general, interesting brain areas responsible for visual-vestibular integration are the Medial superior temporal area (MST), ventral intraparietal area (VIP), posterior partial cortex,

and the superior temporal polysensory area. These areas are sensitive to optic flow. Vestibular signals are primarily transmitted to the vestibular cortex (area 2v, the parieto-insular vestibular cortex, and area 3a) and the deep cerebellar nuclei. Typically, the MST and VIP areas contain vital information of self-motion direction from both the visual and vestibular systems (Murray and Wallace 2011). Specifically, the perisylvian vestibular region, including **parietal operculum (PIVC)** and **posterior insular cortex (PIC)**, could be interesting for examining the involvement of visual-vestibular interactions (Harada et al. 2021). A recent study by Harada et al. found that functional connectivity of the left vestibular seed regions is connected with individual motion sickness susceptibility (Harada et al. 2021); however, whether such result can be extended to individual cybersickness susceptibility needs further validation. It is now understood that gut-brain axis plays an important role in gastrointestinal regulation such as the

initiation and maintenance of nausea and vomiting (Zhong et al. 2021). Since high sensitive individuals tend to have nausea or vertigo sensations when cybersick, studying the gut–brain interaction may be the key to unfold the mystery of individual susceptibility. However, recent studies suggested the complexity of the evolution of nausea since it involves lots of brain areas (Napadow et al. 2013; Zhong et al. 2021). Therefore, many challenges remain before a full understanding of the underlying neural mechanism of cybersickness.

4 Factors affecting cybersickness

We collected papers exploring factors that affect the degree of cybersickness with human subjects. We further assessed the factors studied in those papers. An extension of the classification from the literature resulted in five main factor categories (Fig. 1), which are Content, Interaction, Hardware, Human and Experimental factors (Chang et al. 2018; Davis et al. 2014). The main links between these categories of factors are highlighted in Fig. 3.

4.1 Terminology

The naming and the classification of terms was inspired by previous review papers (Chang et al. 2020; Saredakis et al. 2020; Davis et al. 2014).
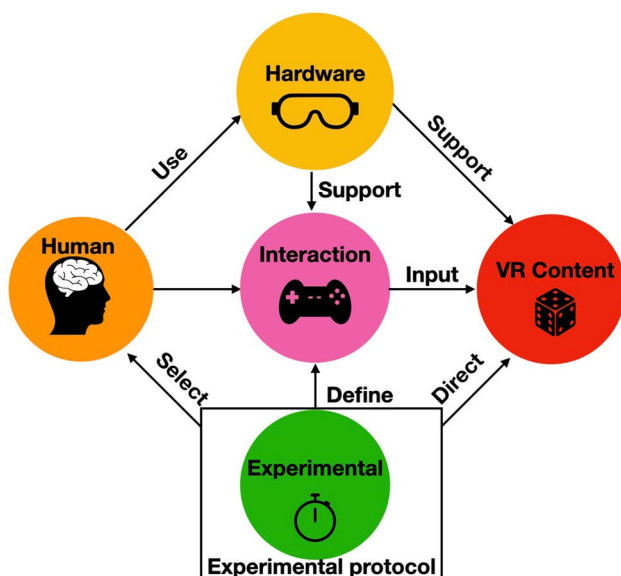

Fig. 3 Links between categories of factors. The participants use the hardware to interact with the VR content, hardware supports VR content and the interaction. The experimental protocol guides the selection of the participants and directs the VR content design

4.1.1 Content

These factors are directly associated with the exposed VR content for users, focusing on the related visual characteristics (e.g., vection, optic flow, VR fidelity, flicker, visual lag, sickness mitigation-oriented features like rest frames, the field of view (FOV) modification, etc.) Generally, content is anything related to what users see in the virtual environment.

4.1.2 Interaction

Interaction-related factors denote to the ones that are associated with how users interact with the VR applications.

– The task-related features (e.g., navigating, exploring or gaming featured, translational or rotational velocity and acceleration)
– The controls of the movement (e.g., controllability and navigation styles) and game-related features (e.g., narration, sound)

4.1.3 Human

Human-related factors refer to the ones that are directly linked to users who get exposed to VR content. We further classify the human factors into two categories: intrinsic human factors and extrinsic human factors. The intrinsic factors mainly include

– Innate demographic characteristics (e.g., age, gender, durability)
– User susceptibility to motion sickness and cybersickness.
– Health-related characteristics (e.g., illness or poor vision). We excluded the papers related to illness factors due to a limited scope of this paper.

The extrinsic features include acquired experience (like video game experience, VR experience, and other simulation experiences).

4.1.4 Hardware

The hardware-related factors typically refer to the technological aspects of the head-mounted display (HMD), which include the field of view (FOV), depth of field, hardware qualities (such as tracking errors, resolution, latency). Another hardware-related factor is motion-coupled devices (such as bike or car simulation controls).

4.1.5 Experimental

Apart from the primary factors mentioned above, the experimental methodology might also influence the severity of

cybersickness. Here, we label the associated ones as experimental factors, including the use of other interventions like drugs, the posture, the duration and repetition of the VR exposure, the trials before VR exposure, and the rest time between trials.

4.2 Content

4.2.1 Navigation profile

Navigation profiles could strongly influence the severity of cybersickness since they are directly linked with the magnitude of optic flow in peripheral vision. Key features are listed as follows (it is assumed that all movements are driven without physical walking):

– **Movement direction:** Translational (forward or backward; Lateral; Up and down) and Rotational (Yaw, pitch or roll axes). Movement direction determines the optic flow direction, which may lead to different physiological changes and symptoms.
– **Moving profiles:** Magnitude of translational and rotational speed and acceleration.
– **Motion locus within the FOV:** Peripheral or central

The optic flow direction has a significant influence on the physiological changes and symptoms elicited during cybersickness as found in paper (Gavgani et al. 2017). Participants reported lower skin conductance levels, longer tolerance time, and significantly lower subjective symptom intensity in backward movement than forwarding movement. This may be because the vestibular system has low sensitivity to backward movements (Gallagher and Ferrè 2018). Generally, the movement along the vertical axis is tested to induce stronger cybersickness than movement along the lateral axis (Pöhlmann et al. 2021; Kim and Park 2020). Researchers also made comparisons between different rotational axes as well as the effects of their combinations. For instance, a pitch axis rotation could induce sickness symptoms faster than a yaw axis rotation (Kim et al. 2020; Terenzi and Zaal 2020), which differs from earlier findings that there is no particular dominant rotational axis over the severity of cybersickness (Lo and So 2001). This could be explained by differences in rotation amplitudes and movement patterns. Furthermore, both papers imply that people vary in individual susceptibility. The ones who are susceptible to cybersickness have lower unease thresholds with higher nausea scores (Kim and Park 2020)). Concerning the effect of combination axes, a combined pitch and roll axes rotation was found to generate more cybersickness than rotation along pitch only (Keshavarz and Hecht 2011; Chang et al. 2020). However, there was no significant difference found between the combination two and three axes (Keshavarz and Hecht 2011). Therefore,

we assume that the brain can hardly distinguish rotations along with two or three-axis, especially when sick.

Considering the moving profile of the VR scene, it has been observed that static scene or constant speed translation could prevent the user from being sick. In other words, the acceleration rate is a key determinant of cybersickness severity (Al Zayer et al. 2019; Chang et al. 2020; Kim and Park 2020). Besides, (So et al. 2001) showed that the level of cybersickness is positively correlated with the increase of speed from 3 to 10 m/s. However, level of cybersickness stops increasing after 10 m/s till a maximum speed of 59 m/s. Agic et al. performed a similar series of experiments with navigation methods and speed ("slow": 4.25 m/s, "medium": 6.37 m/s, and "fast": 8.5 m/s) as main experimental factors (Agić et al. 2020). Although no significant results were found concerning speed levels and the reported cybersickness symptoms, the paper did highlight the need for profiling the clear correlation between symptoms and factors.

Finally, movement occurring in the peripheral vision is claimed to cause more discomfort than the movement in the central visual area (Lin et al. 2002; Ren et al. 2016). A recent study carried out by Pohlmann et al. gained further understanding of the impact of motion direction (longitudinal axis and lateral axis), motion locus within the FOV (center within 20 degrees, periphery from 20 to 30 degrees, or far periphery from 30 to 50 degree) and their interactions on cybersickness (Pöhlmann et al. 2021). Generally, stronger vection and discomfort were rated for the longitudinal axis compared to the lateral axis. Furthermore, for longitudinal movement, far peripheral movement caused more discomfort than the others, whereas, for the lateral movement, the central stimuli caused more discomfort than the other two.

4.2.2 Visual content related

Visual content has a complicated structure and is the primary source of visual inputs. Commonly discussed VR features are Visual content type, visual fidelity, optical flow, rest frame, content FOV manipulation, vection, etc. Among those, adding rest frame and FOV manipulation are strategies to mitigate cybersickness. We discuss them in Sect. 6. Visual content type potentially has a critical influence on cybersickness. In the study conducted by Guna et al. (2019b), Guna et al. (2019a), two types of 360 videos were introduced. The neutral content type has a relatively lower degree of motion, and the action content type has a higher degree of motion. Not surprisingly, the final results indicate that VR content with high dynamic motion features induces more cybersickness than static ones. Additionally, the author identified the SSQ disorientation parameter as the most effective indicator of cybersickness. Anwar et al. applied a multi-factorial design to mix the following factors content

type, camera motion, and the number of moving targets (Shahid Anwar et al. 2020). The content type in this paper is classified as fast, medium, and slow. The camera motion refers to camera movement along the either horizontal or vertical axis. The final results indicated that users are less tolerant to fast motion, vertical camera movement, and videos with multiple moving targets (Shahid Anwar et al. 2020). One study by Shafer et al. examined the effect of different video games on the level of cybersickness. These video games varied in the level of sensory conflict defined by the author: First-person game is more cybersickness inducing, adding rest frame and using teleportation is less cybersickness inducing (Shafer et al. 2019). The author claimed that cybersickness was less reported when users were playing a game with a lower level of sensory conflict. Dennison and D'Zmura explored the effect of induced unexpected visual motion to the visual body on cybersickness. Such visual motion occurred approximately every two seconds and lasted for thirteen frames (Dennison and D'Zmura 2018). Surprisingly, the findings suggest that postural instability does not necessarily correlate with cybersickness. Finally, McGill et al. investigated the influence of visual motion cues on cybersickness with VR headsets when the user drives a car. Motion cues in the paper refer to the projection of actual motion of the car to the peripheral vision of the VR view (McGill et al. 2017). Although the author did not manage to find a proper solution to mitigate cybersickness, an interesting conclusion did emerge that different susceptibility groups need different mitigation strategies (McGill et al. 2017).

Vection(illusory self-motion) may have played a vital role in bringing about discomfort when exposed to VR applications. At the same time, evidence that vection is associated with cybersickness is weak and inconclusive in Palmisano et al.'s paper (Palmisano et al. 2017). Gallagher et al. reported significant proof that vection in VR could change vestibular processing and may account for the after-effects (Gallagher et al. 2020). Risi and Palmisano identified in their study that participants tend to report a higher level of cybersickness when experiencing stronger vection (Risi and Palmisano 2019).

Visual Realism has been a well-researched topic in this field. Toni Kuosmanen et al. studied the impact of low and high visual details of 3D scenes with a within-subject design, and participants experienced the custom-made VR game for 10 min each condition. Hybrid measures – Postural sway, post-SSQ, MSSQ, and FMS were applied. Eventually, they found no significant impact of visual Realism on the level of cybersickness (Kuosmanen 2019), this may be due to the design itself. From the picture attached in their papers (Kuosmanen 2019), the difference is not that salient between the levels. In contrast, a between-group study of Davis et al. argued that more realistic virtual scenes with higher levels of optic flow increased the level of cybersickness significantly (Davis et al. 2015). Unlike Kuosmanen et al., Davis used two commercial roller coaster games and only subjective nausea ratings. Even though the gender factor was well-balanced between groups in Davis's study, the other content factors may differ, such as rotations' magnitude.

Apart from the number of content factors mentioned above, a few studies have explored the cause of cybersickness with a particular focus. Vasylevska et al. investigated the effect of brightness on users' discomfort aiming towards Eye-friendly VR Vasylevska et al. (2019). Three levels that shared the same content were introduced as full brightness, the night mode, and significantly lower brightness. A find-picture difference game was used for the final evaluation. Results suggest that the users preferred bright settings; the darker settings also performed well. No difference was reported on cybersickness level, which maybe because of the static game.

4.2.3 Game features

Additionally, few papers explored some game mechanism features on the level of cybersickness. However, due to the limited number of studies, we cannot generalize their conclusions. Weech et al. investigated the influence of the narration (Either enriched with the verbal narrative context or with minimal narrative context) and personal video game experience (classified by the number of hours per week) on cybersickness (Weech et al. 2020). The enriched narrative context delivered by sound clips was expected to provide more background information about the upcoming VR experience than the minimal condition. The authors characterized regular gamers as participants who reported more than five hours of video gameplay per week, and the rest were classified as non-gamers. As a result, Weech et al. observed that enriched narrative context can enhance presence but failed to find any positive evidence that enriched narrative reduces cybersickness (Weech et al. 2020). Interestingly, they also found a weak interaction effect of narrative factor and video game experience as the positive effect of narration on the reduction of cybersickness could disappear if the users are gamers (Weech et al. 2020).

4.2.4 VR scene susceptibility

Recently, Smith et al. proposed an innovative method to quantify the susceptibility of virtual environments to induce cybersickness (Smith 2021). The method combines visual optical flow, an entropy metric of scene complexity, and a cumulative time-series measure (Smith 2021). The study then compares the known cybersickness attributes such as different roller coaster types, different FOV sizes, and facing directions. The result indicates that the approach can

successfully distinguish the known levels of cybersickness. However, the limitation lies in the passive experience without control or head movement.

4.3 Interaction

4.3.1 Navigation method

Thus far, several studies have investigated the effects of the navigation method on cybersickness. Standard navigation techniques include walking-based (such as natural waking, redirected walking, walking in place (WIP)), spatial steering (e.g., Gaze-directed, hand-directed, body leaning or torso-based, controller-based steering (which ranges from commonly used gamepad or joysticks to other complicated physical facilities like treadmill or chairs.)), selection-based (e.g., teleportation), manipulation-based, other multi-scale virtual locomotion (e.g., flying, swimming and passive steering) (Al Zayer et al. 2018). In order to keep consistency, we standardized the terms from different papers describing the same navigation method. For the innovative techniques, we kept the terms the same as introduced in the original papers. Data from Monteiro et al's paper suggest that walking-based techniques are generally less cybersickness inducing than controller-based steering using a gamepad, with natural walking being the most comfortable (Monteiro et al. 2018). Frommel et al. have examined different controller-based techniques such as teleportation, fixed-point teleportation, gamepad-based steering, and passive steering. Final results showed that teleportation outperforms the others with minor discomfort and more enjoyment (Frommel et al. 2017). A qualitative study by Weißker et al. (2018) compared virtual jumping with gamepad-based steering and teleportation. Although most of the participants show a strong preference for steering, results justify that jumping induced significantly less cybersickness than steering (Weißker et al. 2018). Finally, the comparative study by Mayor et al. (2019) offers an empirical analysis on the effects of four different navigation methods, which included gaze-based fixed-point direction, gamepad steering, teleportation, and natural walking. Results showed that natural walking and teleportation scored comparatively lower than gaze-based and gamepad steering concerning cybersickness.

In comparison, the gamepad stood out as the most acceptable for interaction with the 3D world. To compare the effect of gamepad steering with hand-directed steering (using leap motion) and WIP navigation on cybersickness, Lee et al. (2017) carried out a series of experiments. This study identified that WIP performs the best in terms of presence and cybersickness. Apart from the commonly researched navigation methods, innovative navigation styles kept emerging. For example, perhaps the most severe disadvantage of teleportation is that discrete viewpoint changes often lead to

disorientation (Sarupuri et al. 2017) and reduce the sense of presence (Habgood et al. 2018). In order to address such an issue, Sarupuri et al. invented a "TriggerWalking" locomotion technique to trigger navigation in a virtual environment. They compared with a gamepad, teleportation, and WIP (Sarupuri et al. 2017). The findings of this study suggested that the proposed navigation scores are the lowest in SSQ among all. Habgood et al. (2018) presented an alternative node-based navigation and compared it with commonly used gamepad steering and teleportation. The results reflected that the implemented node-based techniques do not induce more discomfort feelings than teleportation. Nevertheless, it failed the expectation of surpassing teleportation regarding the sense of presence. Coomer et al. (2018) set out to investigate the impact of two newly designed navigation methods (Point-Tugging and Arm-Cycling) and compared them with the classic gamepad steering and teleportation. As a result, the findings implied that both teleportation and Arm-Cycling did not induce significant cybersickness. Results from Żukowska et al.'s paper are in accord with recent studies (Christou and Aristidou 2017) indicating that controller-based steering increased discomfort in VR training applications compared to teleportation (Żukowska 2019). In contrast, a study also claims that teleportation techniques have no advantage over controller-based steering on cybersickness reduction (Clifton and Palmisano 2020). We assume it may be due to variance in individual susceptibility.

4.3.2 Controllability

Previous literature identified that if the user has control over their virtual movement, there would be less cybersick (Venkatakrishnan et al. 2020b, a). However, there is conflicting evidence on such a relationship indicating that the active control is no better than passive viewing on cybersickness (Risi and Palmisano 2019; Mittelstaedt et al. 2018).

4.4 Hardware factors

Researchers have been actively studying the hardware factors in previous review papers (Chang et al. 2020; Caserman et al. 2021; Rebenitsch and Owen 2016). Investigated factors in this category are Display type, Latency, Flicker, etc. Many studies have examined the role of display type on the level of cybersickness (Geršak et al. 2020; Somrak et al. 2019; Mittelstaedt et al. 2018; Guna et al. 2019a). The latest generation HMDs already achieved significantly lower cybersickness. Unfortunately, the issue still exists. Through a meta-analysis, Caserman et al. found that HTC Vive induced statistically lower SSQ scores than the Oculus Rift DK series (Caserman et al. 2021). However, the author claimed that this might be due to the limited sample size of Oculus Rift DK1 studies. Unexpectedly, there

was no significant improvement found in Oculus Rift DK2 compared to DK1. The author even observed higher scores from Oculus Rift DK1. One assumption was that changes in content factors are more impactful than hardware factors (resolutions and refresh rates) between two Oculus Rifts (Caserman et al. 2021). High latency was proved to lead to more cybersickness (Stauffert et al. 2018, 2020; Palmisano et al. 2020; Caserman et al. 2019). Generally, the cause of latency could be hardware limit, the time difference between visual and the physical movement, and tracking delay (Rebenitsch and Owen 2016). Latency should be appropriately measured, reported, and minimized so that it does not impair user experience (Chang et al. 2020; Stauffert et al. 2020). Additionally, latency could be reduced with prediction. However, the prediction could also provoke side effects like over anticipation (Stauffert et al. 2020). To compensate for the limitations of previously proposed theories, Palmisano et al. (2020) attributed cybersickness mainly to the differences in virtual and physical head pose (DVP), especially when there was a large magnitude of DVP and changes over time. The proposed explanation could not decipher the individual susceptibility to cybersickness either.

Finally, with the advance in hardware technology, flicker is almost no longer a threat. However, some researchers raised the attention that there were differences in individual susceptibility to flicker perception (Chang et al. 2020).

4.5 Human factors

The VR experience of individuals from different groups tends to vary with different contents, hardware, or experimental settings. It is likely that each individual experience differently on the same content with the same devices over time. Radical differences among individuals could lead to a discrepancy in findings between groups or publications. As aforementioned, previous literature has explored several human factors like gender, age, past VR experience, etc. Here, we put a great deal of emphasis on the individual susceptibility to cybersickness, which is merely considered in the published experimental studies. Despite the demographic characteristics and personal VR experiences, individual susceptibility in this paper refers to an innate sensitivity to sensory conflicts. Statistically speaking, whether or not it is correlated with gender traits, past VR experience, or motion sickness history is still unclear. Nevertheless, through the inconsistent results from the literature review and our observations during experiments, it is highlighted that the overall tendency of a sample cannot determine the individual susceptibility. The following sections discuss whether a specific human factor is prevalent in the reviewed papers.

4.5.1 Gender

Gender as an important demographic characteristic is one of the most studied human factors, with a few findings indicating that women are generally more sensitive to cybersickness than men (Gonçalves et al. 2018; Al Zayer et al. 2019; Hildebrandt et al. 2018; Rangelova et al. 2020), some reported in detail that only for nausea-related symptoms (Grassini et al. 2021). An early finding claimed that female subjects tend to experience greater sickness because they have a larger field-of-view compared to male (Kennedy and Frank 1985). A recent study by Stanney et al. attributed the non-fitted inter-pupillary distance (IPD) as the main drive and motion sickness susceptibility as a secondary drive for gender difference (Stanney et al. 2020). A follow-up study demonstrated that when females could properly adjust the IPD of the VR headset to fit themselves, the level of cybersickness experienced would be similar to the male. However, heterogeneous findings were also reported as no significant difference between genders in the susceptibility to cybersickness (So and Yuen 2007; Sagnier et al. 2019; Weech et al. 2019; Williams and Peck 2019; Melo et al. 2019; Hsiao et al. 2019; Curry et al. 2020). The following possibilities could result from some discrepancies among studies: Firstly, the individual susceptibility was not pretested before experiment. In general human-involved research, a sample should be representative of the target population (Peck et al. 2020). It is accepted that a larger sample size contributes to more precise results (Abdul Jabbar and Felicia 2015). However, a sample size larger than 100 is barely observed. Peck et al. examined the VR human studies from 2015 to 2019, and the results show that women participants are still under-represented in general human-involved VR research. Peck's paper also indicates that the proportion of females is correlated with the change in the severity of cybersickness across studies. Hence, the sampled groups from papers may differ in overall individual susceptibility. Moreover, the VR content used for experiments also varies among studies. For example, some papers adopt 360° videos with passive navigation (Melo et al. 2018), while others use VR games (Curry et al. 2020) allowing freedom of control. Also, some studies utilize videos or games with little to no acceleration, while others apply VR content with dramatic visual movements. Thus, it is difficult to conclude the effect of one specific factor on cybersickness from the literature due to the inclusion and disparity of other factors. Additionally, those studies shared common flaws in experimental design that we seldom have enough information to identify whether the other human factors are well balanced between groups. To sum up, we agree with the findings in Grassini and Laumann's review that it is still too early to conclude from the literature review that the gender difference has predictive power in cybersickness susceptibility (Grassini and Laumann 2020).

Therefore, there is a need to include and report in detail on genders and associated VR experiences. Moreover, the gender should be balanced, even when the study is not on gender factor (MacArthur et al. 2021).

4.5.2 Age

With regard to age, it is reported that children aged under 12 have the highest sensitivity. The susceptibility declines sharply from 12 to 21 and beyond (Shafer et al. 2017). However, other studies observed that the elderly often showed more severe discomfort than younger ones (Rebenitsch and Owen 2014; Hildebrandt et al. 2018). Recently, Tychsen et al. experimented on 46 young children aged between 4 and 10 with an eagle flight game for a duration of one hour (Tychsen and Foeller 2020). Results indicated that young children tolerate fully immersive 3D virtual reality gameplay without significant side-effects on visuomotor functions. Furthermore, VR play did not induce significant post-VR postural instability or weaken the adaption of the vestibular-ocular reflex. Interestingly, Huygelier et al. experimented on 78 elderly participants with an average age of 74.8 for 2.5 h each (Huygelier et al. 2019). As a result, the self-reported cybersickness was also considered minimal. It is worth mentioning that the eagle flight game is a self-controlled flying experience with both translational and angular acceleration. Dynamic FOV restriction is introduced to reduce cybersickness. On the contrary, the elderly were exposed to a slow-motion game with passive navigation. Sakhare et al. compared both age groups (40 participants in total) in their study, where participants cycled in a virtual park for roughly 10–12 min. It turns out that both age groups shared similar VR experiences without significant differences in cybersickness levels (Sakhare et al. 2019). Unlike the gender factor, the age factor is less studied with the framework of modern HMDs. However, similar conclusions could be drawn from the literature that age difference cannot be a powerful indicator for cybersickness. Also, it is worth mentioning that the gender factor is not balanced in the studies mentioned above.

4.5.3 Past video or VR game experience

Nevertheless, compared to the gender or age factor mentioned above, the better predictor of an individual's susceptibility might be the past 3D game experience, or even more closely, past VR game experience and past VR experience. 3D game experience refers to an active game experience with 3D games on computers, mobile phones, or other game consoles like Xbox and Switch. VR game experience refers to an interactive experience with a VR game. Finally, VR experience refers to a passive experience during 360 videos or movie watching with HMDs. It is worth mentioning that VR game experience and VR experience

are indistinguishable due to the limited description in the literature. Additionally, video game experience is also quite general, as 3D game experience is quite different from 2D. Chattha's paper is the only one specified 3D game experience. Therefore, we strongly encourage future studies to ask questions separately since they can link to the individual difference. Concluding from the studies that investigated the effect of videogame play experience on cybersickness, experienced users have a lower tendency to suffer from cybersickness (Weech et al. 2019; Hunt and Potter 2018; Weech et al. 2020; Grassini et al. 2021). Chattha's result found no evidence that past 3D game experience and VR experience influence cybersickness level. Unfortunately, we did not find any detailed description of how the participants are classified by 3D game experience or VR experience.

Likewise, a few studies assessed past VR experience, and its effect on cybersickness (Sagnier et al. 2019; Marengo et al. 2019; Elwardy et al. 2020; Chattha et al. 2020). Similar to other human factors, reported results are not always consistent. Marengo et al. found that participants who have less VR experience tend to be more cyber sick. Meanwhile, Sagnier et al. reported that prior VR experience has no significant impact on cybersickness. The difference may be because Marengo used a custom-made 3D Pac man game with free movement control. Comparatively, participants in Sagnier et al. paper were involved in an assembly task without locomotion. Elwardy et al. conducted a within-subject study with 360° videos (Elwardy et al. 2020). The participants were clustered into experts, some VR experience users (a few times a year), and novices who had never used HMDs before. The result shows that novices experienced higher cybersickness than the other two groups.

To conclude, we found that the assessment for prior experiences varied among studies and the final results on cybersickness differed. Hence, we encourage future studies to use a standardized method/scale to assess user prior experience. Secondly, 3D game experience, VR game experience, VR experience should be distinguished in the assessment.

4.5.4 Prior motion sickness or cybersickness susceptibility

Motion sickness susceptibility or motion sickness history seems to be another potential predictor of possible individual susceptibility to cybersickness. Among the papers that we reviewed, 10 papers applied a Motion sickness susceptibility questionnaire (MSSQ) in their studies (Rietzler et al. 2020; Hunt and Potter 2018; Cortes et al. 2019; Tiiro 2018; Kuosmanen 2019; Iskenderova et al. 2017; Kaufeld and Alexander 2019; Grassini et al. 2021; Chattha et al. 2020; Grassini et al. 2021). The link between cybersickness and motion sickness history also varies among studies. Rietzler et al., Grassini et al., Kaufeld et al., and Grassini et al. reported MSSQ score as a significant predictor of SSQ score (Rietzler

et al. 2020; Kaufeld and Alexander 2019; Grassini et al. 2021). On the other hand, Tiiro's, Iskenderova's and Chattha's papers found no statistical relationship (Tiiro 2018; Iskenderova et al. 2017; Chattha et al. 2020). The rest of the three papers did not report any further analysis on MSSQ. Apart from the Motion sickness susceptibility, we often ask for prior VR experience or VR game experience in terms of frequency. However, the prior cybersickness susceptibility is a more direct predictor. Keshavarz et al. (2021) developed a visually induced motion sickness susceptibility questionnaire (VIMSSQ) to estimate individual susceptibility. The questionnaire was built by collecting the frequency and severity of different VIMS-related symptoms associated with commonly used devices in daily life (such as TV, smartphones, 3D movie, VR, etc.). However, the final evaluation was conducted with a CAVE or DOME-like big screen simulation. Hence, we cannot directly agree on its validity for VR studies. Rather, we would call for the development of such a questionnaire for cybersickness with HMDs.

4.5.5 Other individual differences

Recently, due to the significant variance in individual differences, including individual susceptibility in the study came into prominence. Apart from the factors discussed above, Widyanti and Hafizhah (2021) recently investigated personality with the HEXACO personality questionnaire. All of the participants were grouped into six potential dimensions, including Honesty-Humility (H), Emotionality (E), Extraversion (X), Agreeableness (A), Conscientiousness (C), and Openness to Experience (O) (Ashton et al. 2004). Final results show that the Emotionality type of participants rated the highest disorientation and oculomotor score (Widyanti and Hafizhah 2021). Fulvio et al. identified that an individual's sensitivity to motion parallax cues could predict the level of cybersickness (Fulvio et al. 2021). The susceptibility was assessed through a 3D motion direction discrimination task.

4.6 Experimental

4.6.1 Duration

One essential aspect of research in cybersickness is the time course of symptoms (Häkkinen et al. 2019; Risi and Palmisano 2019). In a comprehensive literature review of temporal aspects of cybersickness during simulator or VR exposure, Duzmanska et al. identified three significant findings: 1. Though it is not a universal pattern, cybersickness has a high chance of increasing with exposure duration; 2. There is also evidence indicating that the severity of cybersickness will stop increasing when reaching a certain threshold. The adaptation effect was observed in most

studies; 3. Whist evidence is increasing that prolonged after-effects may exist after VR exposure, a consistent empirical picture is missing. Results vary between studies with the shortest of 10 min and longest of 4h (Dużmańska et al. 2018). Hence, when designing a VR experiment, rest time is necessary between trials or conditions to avoid the carry-over effect. However, it also depends on the adaption of each individual and the individual susceptibility to cybersickness. The rule of thumb is to spread sessions or trials over consecutive days due to evidence showing that cybersickness tends to increase significantly between trials in the same day (Risi and Palmisano 2019; Kim and Park 2020). Häkkinen et al. investigated the duration effect with levels of 5 or 10 or 20 min on cybersickness with slow motion 360 videos (Häkkinen et al. 2019). The final results show that cybersickness severity increases between 10 and 20 min and remains the same after 20 min. Finally, Melo et al. conducted a between-group study to investigate different durations (1,3,5 and 7 min) with two kinds of 360 videos (captured video vs. virtual environment) (Melo et al. 2018). Captured video contains real-world scenic views. Participants were positioned in the center of a square and watched the surrounding environment like people and cars passing by. The virtual environment was a temple-like scene modeled by Unreal Engine 4; again, participants were still at a fixed point. Not surprisingly, the final results show no impact of durations on the level of cybersickness. The mean scores of cybersickness were not documented in the paper. Therefore, we cannot assert this, but no or low self-motion perception may be the reason since participants were fixed at a point watching surrounding objects or people moving by.

4.6.2 Posture

Posture is a well-studied experimental factor consisting of three basic levels: seated, standing, and supine posture. (Note: Posture in this paper refers to static conditions.) Previous papers reveal that the seated posture is generally less cybersickness inducing than the standing one (Davis et al. 2014; Hu et al. 2021). However, the supine posture is not fully explored yet with the usage of VR HMDs. Marengo et al. (2019) did a study on measuring the influence of the supine posture with a 3D VR Pacman game. The results suggest that the supine pose triggers more severe symptoms than the seated pose, even in the experienced VR user case. Tian et al. (2020a) evaluated the factors of virtual vertical axis orientation and game types on cybersickness in supine posture. Results reveal that aligning the virtual and the real-world coordinate systems is effective in mitigating VR sickness in the supine posture, especially for games with acceleration.

4.6.3 Other interventions

Iskenderova et al. recently evaluated the **influence of alcohol and placebo** on cybersickness. The results indicate that a concentration close to 0.07 percent of blood alcohol level did not increase the severity of cybersickness (Iskenderova et al. 2017). Narciso et al. examined **smell** as an extra stimulus on cybersickness with a virtual environment designed to train firefighters (Narciso et al. 2019). The final results indicate no add-on effect of smells on cybersickness. Apart from the additional stimulus, **the application of pre-SSQ** (Young et al. 2007; Al Zayer et al. 2019) and **the awareness of potential side-effect** (Almeida et al. 2017) of VR before experiment are also stated to increase cybersickness. Additionally, **sound** was considered as a potential influence in Widyanti's study, sound on and off conditions were evaluated, and no impact was found of sound on cybersickness (Widyanti and Hafizhah 2021). The authors argued that whether the sound is pleasing to participants is important since pleasing sound was previously proved to have a positive effect on cybersickness reduction (Keshavarz and Hecht 2014). Finally, **number of trials** before VR exposure is likely to influence the cybersickness level in the official experiments as well. The hypothesis is that for high-sensitive individuals, it may result in more severe cybersickness later. For low-sensitive individuals, trials may help them adapt to the VR and result in lower cybersickness later. However, These assumptions depend on the duration of the trials and are also associated with an individual's previous VR or VR game experience and other individual differences (such as rate of sensory re-weighting, rate of adaptation during VR exposure, speed of recovery after VR exposure). These individual differences are difficult to measure and require a solid standardized protocol for measurements (Gilbert et al. 2021). In conclusion, the review results on contributing factors indicate that it is difficult to predict individual susceptibility given the factors discussed above. There is no clear association found for any specific factor with cybersickness. We observed that a study often involved multiple factors with a small number of participants, lowering the effect size. Also, the other human factors are not fully-controlled when examining the effect of a specific one, which may be the strong case for the dissonances found in the literature. Finally, some results cannot be easily generalized to the entire population due to the limited number of valid empirical studies.

5 Measurements

Measuring cybersickness, classified as subjective and objective, is essential to its understanding. From an experimental perspective, measurements can be applied before, during, immediately after, and a certain period after the intervention.

Currently, the most popular measurement of cybersickness is the Simulator Sickness Questionnaire (SSQ) developed by Kennedy in (1993). Cybersickness felt by each individual is based on three specific symptom groups: Nausea, Oculomotor, and Disorientation using a 4-point Likert scale with the following labels: None, Slight, Moderate, and Severe. The configuration of scores was suggested by Kennedy et al. (2003) with thresholds like negligible symptoms (<5), minimal symptoms (5–10), significant symptoms (10–15), symptoms that are a concern (15–20) and problematic simulator (> 20). Alternative questionnaires like motion sickness assessment questionnaires (MSAQ) (Gavgani et al. 2017) and motion sickness susceptibility/history questionnaires (MSSQ) (Hwang et al. 2018) were proposed recently. However, it is still inconclusive whether these questionnaires designed for motion sickness or simulator sickness are suitable to assess cybersickness. This can be discussed from two perspectives: (1) the relationships between simulator sickness, motion sickness, and cybersickness; and (2) the validity and reliability of the questionnaire itself. According to Kennedy (Stanney et al. 1997), "the general severity of cybersickness is claimed to be three times greater than that of simulator sickness. The profile of cybersickness is fundamentally different from simulator sickness with disorientation as the dominant symptom, following with nausea and oculomotor as the least". On the other hand, Gavgani et al. (2017) concluded that motion sickness and cybersickness are identical problems while using the MSAQ. Nevertheless, knowledge about the relationship is controversial since different self-assessed questionnaires and Likert scales were used in these previous studies. Recent studies indicate that the SSQ is not applicable for measuring cybersickness due to its psychometric qualities (Stone 2017; Sevinc and Berkman 2020; Bouchard et al. 2007). In addition, they criticized the SSQ for being developed based on data collected through a population of highly trained professionals that differed from the normal population In order to match the characteristics of cybersickness, variants of the SSQ, like the Cybersickness questionnaire (CSQ) (Stone 2017), Virtual reality sickness questionnaire (VSRQ) (Ames et al. 2005; Kim et al. 2018) were developed. Kim et al. (2018) attempted to "re-frame" the questions from the SSQ for the assessment of cybersickness as VRSQ; Kim et al. made a similar effort but induced a bias during the inclusion of symptoms (Kim et al. 2018). Indeed, their VR system only involves games without visual motion. Stone et al. (2017) evaluated three commercial VR applications with 202 participants with no prior experience. As a result, he adjusted the scoring system into three scales (0-none, 1-slight, and 2-moderate). A two-factor structure (Dizziness and Difficulty in focusing) was proposed with nine selected items. Later, Sevinc and Berkman (2020) conducted an experiment to assess psychometric qualifications of the original SSQ

and its variants, CSQ and VRSQ, for measuring cybersickness through publicly available VR applications and HMD. They found that symptoms in SSQ did not correlate sufficiently in repeated experiments due to users' adaptation or self-induced cybersickness. Instead, VRSQ and CSQ were found to provide better measures of cybersickness in terms of validity and reliability. The results were supported by Cid et al. evaluating the validity of VRSQ with a rock climbing simulator Del Cid et al. (2021). However, whether the games adopted in the evaluation are representative enough requires further examination. For example, Sevinc et al. adopted multiple games in the study (Sevinc and Berkman 2020). Only one of the games has both joystick-controlled translational and rotational movement. Five of them do not contain any form of translational movement nor locomotion. Most of the empirical studies that we reviewed adopted SSQ as a measuring tool. Even though studies have endeavored to revise SSQ to better adapt to cybersickness, there is still a lack of a more solid empirical validation of these variants. Additionally, a subjective measure during the VR exposure, the Fast Motion sickness Scale (FMS), was also frequently applied at periodic intervals (McHugh 2019; Weech et al. 2020; Clifton and Palmisano 2019) with one simple question asking to rate cybersickness from 0 = 'no sickness' to 20 = 'frank sickness' (Keshavarz and Hecht 2011). A recent trend for applying such questionnaires is to embed them with in-game designs (Alexandrovsky et al. 2020) (Tables 2 and 3).

5.1 Cybersickness susceptibility questionnaire

Similarly to the well-established Motion sickness susceptibility questionnaire, the cybersickness susceptibility questionnaire (CSSQ) was proposed to construct demographic data, health, fitness, and motion sickness susceptibility (Freiwald et al. 2020). The questionnaire was later evaluated with a pilot study that included 24 participants showing a positive correlation between CSSQ items and cybersickness perceived during a virtual roller coaster exposure. Likewise, Keshavarz et al. introduced the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) (Keshavarz et al. 2021). This questionnaire is more comprehensive as they reviewed

Table 2 Paper using ECG to record heart rate and investigate its relationship with level of cybersickness

Paper	Description of VR content	Duration	Number of participants (NOP)	Correlation with cyber-sickness
Guna et al. (2019b)	360 Videos including a neutral content with low motion and an intense one with roller coaster ride	110s each video	26 (3f)	No significant
Gavgani et al. (2017)	Virtual ride on a roller coaster	15 min	14 (8f)	Positive
Wibirama et al. (2018)	Two stereoscopic 3D movie (1. A city walkthrough movie includes up, down, turn left, and turn right motions with a moderate amount 2. A roller coaster movie contains vigorous dynamic motions with a stronger perception of vertical vection)	15 min	40 (8f)	Positive
Niu et al. (2020)	Two VR videos (content not specified)	30 min	30 (12f)	Positive
Garcia-Agundez et al. (2019)	A VR shooter (Quakespasm Rift)	15 min	13 (2f)	Positive

Table 3 Paper using EEG to record brain activities and investigate its relationship with level of cybersickness (NOP stands for number of participants)

Paper	EEG features	ERPs analysis	NOP	Correlation with cybersickness (Interesting Brain areas)
Li et al. (2020)	EEG rhythm energy ratios of delta, theta, alpha, and beta	Yes	24 (5f)	Positive (Not specified)
Arafat et al. (2018)	Beta, Theta, Delta and Gamma powers	Yes	16 (13f)	Positive (Not specified)
Jeong et al. (2019)	Alpha, Beta, Theta, Delta powers	Yes	25 (12f)	Positive (Not specified)
Naqvi et al. (2015)	Delta, Theta, Alpha, Beta powers	Yes	60 (NA)	Positive (Decrease in theta power in frontal region), decreased relative beta power in temporal region)
Heo and Yoon (2020)	Delta, Theta, Alpha and Beta powers	Yes	28 (12f)	Not significant relations (Not specified)
Lim et al. (2021)	Beta , Delta, Theta, and Alpha , Gamma	Yes	21 (0f)	Positive (frontal and central lobe)
Krokos and Varshney (2021)	Delta, Theta, and Alpha	Yes	44 (13f)	Positive (Not specified)

the frequency of common sickness symptoms when using different visual devices such as TV, smartphone, 2D movies, 3D movies, video games, simulator and VR. Twenty-three participants had involved in the evaluation session and final results indicate a correlation of 0.60 between VIMSSQ score and SSQ score. This questionnaire could still be adjusted for VR sickness with more focus on the 3D games and VR content (passive and active control).

5.2 Administration of SSQ in action

Bimberg et al. made a remarkable effort to review the usage of SSQ in the previous literature with an illustration of the critical challenges during application of SSQ in virtual reality research and provide important insights for future studies (Bimberg et al. 2020). First of all, it is reported that different computation variants of the total SSQ score and its sub-scales out of the raw values can be observed among studies. Secondly, the author stressed that repeating the questionnaire could lead to a higher score in the post-SSQ (Young et al. 2007). Therefore, applying a pre-SSQ should not be avoided if different conditions are tested with repeated measures involving the same participants. Thirdly, the configuration of SSQ scores introduced by Kennedy et al. was derived from a sample of military aviators, who might be less susceptible to cybersickness than the general population. Hence, the original configuration of symptoms is indeed not representative of a more general population. Finally, the reporting details of SSQ scores and analysis varied greatly among publications (Bimberg et al. 2020). Therefore, it is suggested to report means, medians, and standard deviations for all sub-scales and the total score. Such a detailed report can benefit the understanding of the configurations of SSQ scores and provide insights into the symptom profiles elicited by an experimental condition. Here, we want to emphasize the importance of applying a pre-SSQ or applying a pre-examination of subjects' health conditions with the following highlights: (1) unlike Kennedy's study, the sample size is usually not big enough to be treated as a population that could be further used as the baseline. Applying only the post-SSQ is based upon the assumptions that participants are in their "best state of fitness" without any kinds of discomfort before exposure (Bimberg et al. 2020; 2) Currently, there is no optimal way to solicit information about the subject's physiological status before an experiment; (3) many experiments are performed across multiple sessions on different days; thus, we cannot ensure that the participant has the same condition for both days. For example, a recent paper from Tian et al. detected different pre-states across different conditions via pre-SSQ (Tian et al. 2020).

5.3 Objective measurements

In addition to subjective measures, given the influence of cybersickness on human bodily functions, it comes as no surprise that physiological measures have often been employed for its detection and prediction. Past work attempted to link physiological data such as: Electrocardiogram (ECG) (Terenzi and Zaal 2020; Kim et al. 2005; Katsigiannis et al. 2018; Dennison and D'Zmura 2017; Magaki andVallance 2019; Stanney et al. 2020), Electroencephalogram (EEG) (Stanney et al. 2020), Electrodermal Activity (EDA) (Stanney et al. 2020) and electrogastrography (EGG) (Matsuura and Takada 2018); with the estimation of different levels of cybersickness symptoms. Unlike questionnaires, such measures can capture each participant's dynamic changes of physiology during VR exposure without interrupting the experience. Studies have also included multi-modal systems, where multiple physiological measures are explored and compared for the task of cybersickness detection (Kim et al. 2005). However, the accuracy of physiological measurements lies in the quality of each sensor, its positioning, and user movements (Lopes and Boulic 2020). When using physiology, questionnaires also tend to be used in conjunction with such objective measures. The reason is that physiological signals can be ambiguous because few contexts can infer that certain bodily reactions are directly correlated to cybersickness or other potential factors present in the experience (LaViola 2000). Unsurprisingly, the findings vary among studies.

– *Heart rate:* Heart rate is mainly captured by ECG. It was reported that subjects who suffered more severe cybersickness had a lower heart rate in Garcia-Agundez et al. (2019). In contrast to the results from Garcia, an increase in heart rate was found in sick participants in Gavgani 's study (Gavgani et al. 2017). Interestingly, both an increase and decrease of heart rate were observed in Wibirama's paper (Wibirama et al. 2018). No significant correlation was found in Guna et al. (2019b). We present more details in Table. 4

– *EEG*: According to the sensory conflict theory (Oman 1989), cybersickness was developed during the integration of visual signals and vestibular signals in the cortex. Through EEG, electric impulses or waves in the brain can be captured. Observed frequencies are mainly categorized in four groups—delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz) and gamma (> 30Hz) (Arafat et al. 2018). Changes in the power of different frequency bands can reveal the evolution of the brain activities of participants. Some papers reported that the gamma-band power was positively correlated with the level of cybersickness (Lin et al. 2002; Wibawa et al. 2019). Other papers recommended that beta and theta

Table 4 Paper using eye trackers to record eye movements and investigate its relationship with level of cybersickness (NOP stands for number of participants)

Paper	Eye movements	VR content	NOP	Correlation with cybersickness
Wang et al. (2019)	Eye blinks and other eye movement(Fixation)	Not mentioned	105 (NA)	Relationship between VIMS and eye fatigue is insignificant
Lopes et al. (2020b)	Eye blinks	Custom made puzzle game with choice of locomotion(standard translational and rotational displacement and teleportation)	34 (12f)	Inconclusive, but indicate a positive correlation between blinks and increased cybersickness
Dennison et al. (2016)	Eye blinks	Free source game by the Source Engine with standard locomotion	20 (6f)	Inconclusive, but indicate a positive correlation between blinks and increased cybersickness

frequencies were reliable for detecting cybersickness (Pane et al. 2018; Khoirunnisaa et al. 2018). Event-based potentials (ERPs) analysis was also commonly applied; it is a measure of brain activities during a potential cybersickness triggered event or time scope (such as turning, or translational acceleration, etc.).

– *fMRI and PET imaging* Functional magnetic resonance imaging (fMRI) and Positron emission tomography (PET) were frequently used in studying brain activities during virtual navigation, and vection (Schöberl et al. 2020; Ashiri et al. 2020). Especially PET imaging as a newly developed technology can measure neurogenic activity and changes in metabolic processes. Therefore, those advanced technologies could enable a more profound understanding of the visual-vestibular integration process on the neurological level. However, performing navigation task inside fMRI has strong constraints like posture and limited movement. Therefore, to study cybersickness in fMRI needs to take limitations into account in experimental and VR content design.

– *Skin conductance:* Skin conductance level (GSR) is also frequently reported in previous literature. However, results differ among studies (Terenzi and Zaal 2020; Katsigiannis et al. 2018; Guna et al. 2019b; Jung et al. 2021). While some reported a strong correlation between skin conductance level and cybersickness (Guna et al. 2019b), others observed an increase but claimed that it was primarily due to the increased arousal, not to cybersickness (Dennison et al. 2016).

– *Stomach activity:* EGG is a promising way to record electrical activities of stomach muscles by the placement of surface Ag/AgCl electrodes over the stomach (Kim et al. 2005). Changes in stomach activities may reflect a reaction by the autonomic nervous system to an uncomfortable environment (Cheung and Vaitkus 1998). A previous study identified that tachygastric rate increases with cybersickness and bradygastric stomach activity decreases (Dennison et al. 2016). However, the duration of the VR exposure (3 min) in this experiment is inadequate as the EGG signal is slow, with an average of 3 cycles per minute. Potential indicators from the EGG signal are not limited to the changes in the ratio of gastric frequencies. A recent study from Gruden et al. found that the increase in the Dominant frequency (DF), the percentage of Power spectrum density Crest factor (CF), and a decrease in high power spectrum density (FSD) are closely linked to cybersickness (Gruden et al. 2021). Interestingly, an increase in EGG amplitude co-occurred with reported nausea. The study consisted of three 15 min recordings of EGG (one baseline, one straight highway drive simulation with low traffic in VR, and one driving simulation in VR with more vehicles leading to more dynamic responses). As a whole, EGG is not frequently used yet. We encourage more researches to explore the EGG signal and its correlation with cybersickness. The brain–gut interaction will also be interesting for further investigation (Koch 2014).

– *Eye related behaviors:* Dennison et al. found that the changes in blink rate are positively correlated with cybersickness severity. Dennison et al. (2016). However another paper by Lopes et al. had inconclusive findings (Lopes et al. 2020a). Gaze direction was also examined in previous papers, but no conclusive correlation was found.

– *Posture sway behaviors:* Postural sway or postural instability is one of the possible consequences when being cybersick. It is often measured by a force plate to assess how the body center is dynamically changing (Weech et al. 2018). Recently, a lot of studies considered using postural sway as objective measures (Aldaba et al. 2017; Cortes et al. 2019; Kuosmanen 2019; Kim and Kim 2019; Dennison and D'Zmura 2018; Rebenitsch and Quinby 2019; Litleskare 2021). A positive correlation was found between postural instability and level of cybersickness.

– *Electrovestibulography:* Understanding Visio-vestibular interactions is key to cybersickness. However, little was known to its etiology base because the vestibular system is located deep inside the inner ear, making it difficult to measure (Brown et al. 2017). Fortunately, a non-inva-

sive technology called electrovestibulography (EVestG for short) was developed to measure and analyze vestibular responses under specific manipulations (Ashiri et al. 2021). By comparing the stationary segment with the dynamic ones (e.g., rotations or up and downs) in a VR roller-coaster ride, Ashiri et al. observed that vection together with the concurrent stress or anxiety factor can stimulate vestibular activities when physically still (Ashiri et al. 2021, 2020a). Furthermore, through a comparative study of physical only and visual-only stimuli, Ashiri et al. found an increase in efferent vestibular activity when participants are stationary watching the virtual visual stimuli. The increase may be due to unreliable visual inputs activating the sensory reweighting system in the cerebellum and shifting the sensory weight to a more reliable system (vestibular) (Ashiri et al. 2020b, a). Interestingly, Ashiri et al. also explored the effect of different color stimuli on vestibular responses. The result showed that the vestibular system responded differently to the different colors and was also sensitive to the intensity of the blue color. Simply stated, the higher intensity, the larger responses in the vestibular system (Ashiri et al. 2019).

6 Methods to mitigate cybersickness

Inspired by the sensory conflict theory, researchers have developed various strategies to reduce or eliminate conflicts between senses. Those methods can be classified into three types of action: (1) reducing the influence of visual cues; (2) eliminating visual cues; and (3) adding vestibular cues matching visual cues.

6.1 Field of view reduction and blurring

In previous work, it has been suggested that a wider field-of-view (FOV) can often help its immersive capabilities and improve the performance of accomplishing tasks in virtual environments (Caserman et al. 2021). However, using wider FOVs enables more prevalent optic flow in the users peripheral vision, which commonly leads to cybersickness (Lin et al. 2002; Patterson et al. 2006; Ren et al. 2016). Unsurprisingly, the manipulation of FOV has become one of the most promising strategies of tackling cybersickness within the literature (Kala et al. 2017; Teixeira and Palmisano 2020). The basic goal is to reduce optical flow of the peripheral area with the intent of mitigating cybersickness. This methodology has seen itself implemented in a lot of commercial VR applications such as Google Earth (Käser et al. 2017) and Stormland (*Insomniac Games*, 2019). The main

drawback of this methodology is that it heavily depends on the implementation and how the user interacts with the environment itself, as it can potentially induce information loss (Berhe et al. 2021; ShiRongkai et al. 2021; Lee et al. 2017; McGill et al. 2017). To improve this issue, Fernandes and Feiner introduced a dynamic FOV technique consisting of constraining the FOV through a black soft-edged circular cutout (Fernandes and Feiner 2016) (this technique is also called vignetting). More specifically, the circular mask bound with the camera softly shrinks towards the center of the camera view when the user moves while growing back to its original size if movement stops. This study verified the effectiveness of dynamic FOV reduction on mitigation of cybersickness without a trade-off of presence. Kala et al. further developed this idea by hybridizing this FOV mitigation technique with a static and dynamic process based on visual content analysis (Kala et al. 2017). First, they estimated sickness by combining the obtained motion information from each frame using a feature tracking algorithm, a head-movement-based method for measuring postural stability, and a sickness model obtained experimentally. A dynamic FOV reduction in the vertical axis is then applied based on the estimated sickness level. The authors observed a significant decrease in cybersickness compared to previous work.

6.1.1 FOV reduction trigger method

Dynamic FOV restrictors can be influenced by motion characteristics such as velocity, acceleration, or the magnitude of optical flow (Kala et al. 2017). Norouzi et al. (2018) assessed two different vignetting techniques (velocity-based and acceleration-based) as means to alleviate cybersickness during head movements. However, the results generally indicate that the vignetting methods did not reduce cybersickness for most participants but resulted in a significant increase in symptoms. The authors claimed that these contradictory results might have arisen due to the different input schemes (such as controllers) used. Similar results were found in Brummet et al.'s study on different dynamic FOV reduction techniques applied during rotational movement (Brument et al. 2020). It may be due to the reason that the central area triggers more discomfort than the peripheral area during lateral motion (Pöhlmann et al. 2021). Different methods to trigger FOV reduction were proposed in previous studies. Generally, those methods involve the extraction of critical features from the VR scene. Here we listed the existed methods in Table 5.

6.1.2 FOV features

We summarize the following detailed features related to the visual design of FOV restrictors that could potentially influence the user's comfort and experience. Some are

Table 5 Key features extracted to trigger FOV reduction

Paper	Description of key features	FOV type
Lim et al. (2020)	Translational velocity, acceleration, Rotational velocity, and acceleration.	2D dynamic restrictor
Bala et al. (2021)	Timestamp, frame number, tracking position, camera rotation, and the number of critical points/landmarks found/tracked using Visual Simultaneous Localization and Mapping (visual SLAM) and peripheral optic flow	2D dynamic restrictor
Yamamura et al. (2021)	Hemoglobin concentration level	2D dynamic restrictor
Zielasko (2021)	Subject's health score in real-time	2D dynamic restrictor

already explored, while some are our assumptions. **Size of FOV** represents the diagonal angle of the displayed FOV (Hopper et al. 2019). Is there a best size for minimum cybersickness without hindering spatial navigation? Kala reported that cybersickness decreased to its minimum when FOV decreased to 60 degrees. The black regions in the periphery area would become noticeable if the FOV continued decreasing to 45 degree (Kala et al. 2017). However, the effect of FOV size is also influenced by the content (e.g., moving profile and direction) (Chen et al. 2021). Moreover, its effectiveness may also vary among individuals. Another researched feature is the **transformation of FOV** in real time. Static restrictors may reduce the sense of presence. However, dynamic restrictors may be less effective on cybersickness reduction if the outward animation is not appropriately applied (see explanation below). In Kala's study, static restrictors reduced 31.4% discomfort, while dynamic restrictors achieved a 28.8% reduction (Kala et al. 2017). The **direction of the FOV reduction** is also interesting to explore. The human visual system has a broader FOV along the horizontal direction than the vertical one. Preliminary results show that the FOV restriction along the horizontal direction reduces the immersion level more than the vertical one (Kim et al. 2018). Since dynamic FOV restrictors outperform static ones, the **outward fading animation** used when restituting the original FOV becomes our concern. The style and speed of such animation could also have an impact on the level of cybersickness due to the induced expanding optic flow (Bala et al. 2021; ShiRongkai et al. 2021). Likewise, **coupling rest frame design** is another interesting combination for cybersickness mitigation. There is a positive effect of combining the display of a rest frame when dynamically reducing the FOV, such as in Google Earth VR (Käser et al. 2017). Finally, **3D FOV design** is an experimental idea from us. A 2D FOV restrictor is a 2D mask in the image plane, whereas a 3D FOV restrictor exists in the 3D virtual environment. We assume that 3D FOV restrictors can lead to a higher presence than 2D restrictors and reduce cybersickness if appropriately designed.

6.1.3 Blurring techniques

The human eye naturally perceives the surrounding environment with variations in blurs. The variation in blur can be classified into two categories: (1) the objects in central retina are salient, and the peripheral area is blurred; (2) the objects in the close distance are salient and blurred at a far distance. In order to mimic these two blur effects in VR, researchers explored two blurring solutions: non-salient blurring (Nie et al. 2019), and depth-of-field blur (DOF blur) (Hussain et al. 2021; Chen et al. 2021). Nie et al. (2019) presented a novel method by blurring the non-salient area dynamically. The idea is to detect the non-salient object in the scene and blur them in the displayed image. The experimental data demonstrate that participants experiencing dynamic blurring report significantly less sickness than the condition without blurring. On the other hand, Chen et al. (2021) proposed a novel texture blur technique that combined DOF blur, object weighting, and blur distance together. Though no significant differences in discomfort score between with and without texture blur were found in the experiments, the results still showed a decrease in the mean discomfort score. The authors indicated that the navigation style determines the effectiveness of such a mitigation method (e.g., it cannot help to decrease the discomfort in rotational movement). Hussain et al. (2021) combined two kinds of blur effects, where the overall scene was divided into three sections corresponding to the foveal, near, and mid peripheral regions, and added filter accordingly. The final results indicate a significant reduction of cybersickness with Foveated Depth-of-Field blur. Furthermore, the study also compared the susceptibility of cybersickness with the proposed method between different age groups and genders. The authors observed that the older population was more susceptible to cybersickness without the blurring effect, while no such observation was made between genders.

6.1.4 Individual susceptibility

Recently, individual differences have been taken into consideration in FOV studies, especially gender. It was claimed that women were more susceptible to cybersickness. Specifically,

Zayer et al. (2019) compared both gender groups based on the influence of FOV masking on cybersickness and spatial navigation. In this study, the restrictor is a 2D black mask with a circular cut off in the middle. The authors observed that FOV manipulation could help mitigate cybersickness, despite no difference being observed between genders. This was also observed in a follow-up study on spatial navigation, where the FOV mask did not hinder spatial learning in either of the groups (Adhanom et al. 2021a). Adhanom et al. compared the effect of foveated FOV restrictor with a fixed FOV restrictor on cybersickness and user experience (noticeability of FOV) in their paper (Adhanom et al. 2020). The FOV restrictor is as the same design as Zayer's. The result indicated that the foveated FOV restrictor did not have a better performance than the non-foveated one. Evidence suggests that spontaneous postural instability could be a potential predictor for individual susceptibility during VR gameplay (Teixeira and Palmisano 2020).

6.2 Eliminating the visual cues influence

6.2.1 Teleportation and snap turn

Navigation is one of the essential tasks in VR applications and games. Different locomotion styles have been explored and introduced to the virtual environment to achieve navigation purposes (Al Zayer 2018; Nilsson et al. 2018). However, the choice of the locomotion style would heavily impact the user experience, inducing nausea and disorientation or influencing the level of presence (LaViola 2000). Recently, developers have been actively exploring a wide variety of locomotion techniques to deal with cybersickness. Teleportation is a popular selection-based locomotion strategy that claims to be promising as it can reduce optic flow via inconsistent displacement. Although its effectiveness remains disputable (Farmani and Teather 2020), it is still the most common choice for a comfortable VR experience from a Longitudinal study conducted by Porter and Robb (2019).

Weißker et al. (2018) presented a detailed classification scheme of teleportation techniques with decomposing it into four subsequent steps: (1) target specification; (2) pre-travel information; (3) transition; and (4) post-travel feedback. These subsequent steps provided a clear guidance for designing teleportation. The design considerations of those four steps count have impact on the user discomfort and experience. For instance, Moghadam et al. investigated the effect of different scene transitions techniques in teleportation (instant and fade to black) and different viewpoint transition styles (rotation only, translation only, and both) on user comfort and ability to maintain spatial awareness (Moghadam et al. 2018). These techniques were tested on two scenes: a Viking village style with less color contrast and a cartoon fort with more color contrast. The final results

reveal no impact of these factors on cybersickness, which may be due to the small sample size and the fact that the cartoon fort scene with a high-intensity light blue ground could lead to more cybersickness than initially expected.

Researchers have also introduced a discrete viewpoint control solution named snap rotation or rotation snapping to combat cybersickness for rotation movements. Farmani and Teather used a customized first-person shooting game to evaluate the effect of snap rotation on cybersickness (Farmani and Teather 2018). They chose to snap rotate only when the user was turning right or left with rotation speed over a threshold of $25°/s$; continuous rotation was then replaced with a fast-fading transition animation between $22.5°$ increments in such a context. Not surprisingly, the overall results showed that the snap rotation significantly reduced the level of cybersickness. Meanwhile, the authors pointed out the limitations of such a technique as being a tradeoff between user comfort and realism. Moreover, participants' reports also imply a possible increase of disorientation in the initial stage of gameplay and a decrease in presence. As a follow-up, Farmani and Teather continued to evaluate the effectiveness of both rotation snapping and translation snapping (similar to short-distance teleportation) (Farmani and Teather 2020). A one-meter translation distance was considered to be preferable and applied in the formal experiment. Test results presented substantial evidence of both translation and rotation snapping alleviating cybersickness compared to the continuous locomotion methods. Interestingly, the authors interviewed participants for their susceptibility to cybersickness and motion sickness history before the experiment. However, no further analysis was performed along with the obtained experimental data.

Apart from the aforementioned positive results, the discrete locomotion techniques also face criticisms due to controversial reports as discussed below. In 2019, Clifton and Palmisano conducted an experimental design to compare the effect of two controller-based locomotion (Teleportation and steering) on cybersickness (Clifton and Palmisano 2019). On average, teleportation produced less cybersickness than the steering locomotion based on the SSQ scores. However, the authors argue that teleportation is not a complete solution to reduce cybersickness since the postural sway analysis speaks against the SSQ results, and 38 percent of participants reported being sicker with teleportation. They conclude that the individual sensitivity to disorientation might be the reason. Likewise, Ryge et al. (2018) presented a between-subject study comparing the snap rotation to smooth rotation. In this experiment, participants have to complete four interactive challenges in a puzzle-like VR game. The final results indicate no significant difference between the two rotation strategies. Roughly, the snap rotation with much fewer details of the experiments induced slightly lower cybersickness than the continuous rotation.

Thus, we cannot reject the claims that discrete locomotion techniques is an effective solution to reduce cybersickness during travel in virtual environments. Nevertheless, we support the notion that the choice of locomotion strategy should be adaptive to individual susceptibility.

6.2.2 Rest frames

Rest frames help users visually remain fixed about the real world to eliminate the visual movement illusion. Our assumption is that the design of the rest frames (such as position, size and color) could also lead to different results in cybersickness reduction. Cao et al. investigated the effect of static and dynamic rest frames on cybersickness reduction. The static rest frame was designed as a latticed Palisade along the vertical direction. Unlike a complete FOV reduction, the user can still see through the rest frame. Based on the static one, the authors then introduced the dynamic rest frame, where the opacity of the rest frame changes in response to visually perceived motion (Cao et al. 2018). The final results showed that both the static and dynamic rest frames effectively reduce discomfort for users compared to without. Wienrich et al. presented a study measuring the virtual nose as a rest frame on cybersickness and game experience (Wienrich et al. 2018). The idea was to test the validity of an unnoticeable rest frame on the reduction of cybersickness. As a result, the usage of a virtual nose reduces cybersickness while not affecting the game experience. Luks and Liarokapis also investigated the rest frame in the form of a cockpit, and a radial object right in front of the first-person view (Luks and Liarokapis 2019). Analysis of the SSQ scores showed no significant difference between the rest frame group and the control group. This may be because the rest frame is placed in the middle of the camera, while the horizontal peripheral vision is barely covered. It may also be due to the between-group variances.

Finally, there is an interesting study from Luks and Liarokapis who examined the effect of different cybersickness mitigation tactics, including three different designs of an optical path, a rest frame, and the combination of the two. The visual path is achieved by placing visual marks along the predefined trail, and the rest frame is ladder-shaped. The final results show that the combination of both visual path and rest frame is optimal among all to reduce cybersickness (Luks and Liarokapis 2019).

6.3 Match the sensory inputs

If we recall the sensory conflict theory (Oman 1989), the conflict often happens when the visual system perceives a motion that the vestibular system does not sense (Davis et al. 2014). Thus, to eliminate the mismatches between these two sensory inputs, it would be logical to stimulate the vestibular system explicitly.

6.3.1 Motion coupled devices

There have been studies on using motion-coupled devices to reduce discomfort (Ng et al. 2020; Al Zayer 2018; Venkatakrishnan et al. 2020b). Such devices are often developed on a motion-inducing platform (Ng et al. 2020), providing vestibular cues to harmonize the visual cues in the head-mounted display. Walking devices like treadmills, step-based devices, and low-friction surfaces have already been commercialized (Al Zayer 2018). Driving simulator related devices (e.g., cars and bikes) are also commonly used (Venkatakrishnan et al. 2020b; Hansen et al. 2019; Vailland et al. 2020).

Ng et al. examined whether coupling physical motions to visual stimuli in VR could reduce the discomfort with a virtual boat simulation (Ng et al. 2020). Results showed that when users were placed under a visual-vestibular synchronized condition, their subjective score of cybersickness decreased, while their comfort level of the overall experience increased. Venkatakrishnan et al. (2020b) investigated the influence of the presence/absence of motion control on the onset and severity of cybersickness in an HMD-based VR driving simulation. Final results indicated that participants in the driving condition experienced higher levels of cybersickness than participants in the physical motion paired condition.

In general, motion-coupled devices could have a significant effect on reducing cybersickness. However, the positive result is not always ensured. Kaufeld and Alexander investigated the user experience with a motion platform coupled with VR exposure. Unfortunately, a difference between the two conditions with natural motion and without could not be observed after exposure (Kaufeld and Alexander 2019). The authors concluded that the individual susceptibility difference might be the reason. Therefore, VR locomotive controller selection was suggested to be customized to a target population's characteristics to reduce user cybersickness (Aldaba and Moussavi 2020).

6.3.2 Direct stimulation of the vestibular system

Apart from the motion-coupled devices, researchers have come up with solutions to directly stimulate the vestibular through noisy galvanic vestibular stimulation (GVS) (Sra et al. 2019; Gardé et al. 2018; Weech et al. 2020) and proprioceptive systems through vibration devices (Wang and Rau 2019).

Sra et al. invented a lightweight wearable GVS device to help reduce cybersickness (Sra et al. 2019). The GVS can function directly to the user's vestibular system through

electrodes attached behind the ears. Through eliciting the vestibular reflexes, it is believed that the inputs of vestibular and visual could be synchronized (Aoyama et al. 2015). Notably, the wearable device supported three different types of vibration simulation: electrical, caloric, and bone conduction, which could potentially simulate different kinds of movements in VR (e.g., flying, boating, driving, or watching 3D videos). Typically, electrical stimulation is known to mimic vestibular cues by providing a sense of linear acceleration in otoliths and a sense of angular acceleration in semicircular canals (Kim and Curthoys 2004). The final results showed a remarkable reduction of cybersickness and enhancement of presence with GVS than without.

Weech et al. (2020) did a similar study examining the effect of noisy GVS on cybersickness severity in VR. Comparatively, the duration of exposure to VR content(50 min) was much longer than Sra et al. (2019) (3 min). Interestingly, the final results differed between the self-reported questionnaires used during (FMS) and after the exposure (SSQ). While the FMS scale revealed a significant reduction of cybersickness in the intensive condition, the SSQ results did not differ between the two groups (with GVS and without). The reason for this discrepancy between measurements remains unclear. The authors also pointed out that this reduction effect quickly disappeared (around 3–6 min) after further VR exposure, indicating that sensory adaptation did not persist after stimulation was terminated.

To sum up, we conclude that GVS as a newly established solution still requires further research. Also, currently, studies only consider the gender factor during cybersickness mitigation. However, other human factors, especially innate individual susceptibility, are still poorly understood.

7 Prediction of cybersickness

As machine learning technology advanced, researchers have proposed solutions to predict cybersickness. Previous work demonstrated the viability to predict cybersickness (Padmanaban et al. 2018; Kim et al. 2017; Jin et al. 2018). To improve user satisfaction with VR applications, it is important to develop solid objective metrics that can analyze and then predict the level of VR sickness when a user is exposed to VEs. However, questions that await to be answered in future studies are (1) what features or inputs should be included in prediction to ensure high accuracy? (2) What combinations of factors and features are needed to predict individual susceptibility? Rebenitsch and Owen offered some preliminary insights in their paper (Rebenitsch and Owen 2021). They proposed three different models, which are (1) Demographic cybersickness model (DCM) that only includes human factors, (2) System cybersickness model (SCM) that excludes the human factors, (3) and Prediction

cybersickness model (PCM) that includes all five kinds of factors. Ideally, DCM and PCM can be used to predict individual susceptibility. From our review, most of the papers (13/17) considered content factors during the data collection stage; human factors are getting attention with a ratio of 6/17, followed by hardware factors (4/17), interaction factors (3/17), and experimental factors (1/17). Most of the papers created their database by recruiting test subjects and recording data through several VR exposures. Two of them used existing database (Kim et al. 2020; Lee et al. 2019). We sincerely call for establishing a standardized database for future experiments, which shall include a variety of VR contents differentiated by content factors. Another critical limitation is that there are only two papers that evaluated their models with test subjects (Kim et al. 2020; Hu et al. 2019). Not to mention that the predictions are offline. Additionally, what needs to be emphasized is that the included factors are not fully equal to the inputs from the prediction model. For example, Islam et al. (2020) used both the FMS score and FMS-labelled physiological signals as inputs for training the model but considered different VR content during recording. A majority of nine papers used content-related factors, especially content type, scene movement, optic flow map, as inputs to the model. Seven papers used physiological data as inputs. Subjective ratings were either directly used as inputs or used to label the physiological signals; more details are provided in Tables 6 and 7. Our review shows that including physiological data for training results does not ensure high prediction power. However, Yildirim's review (Yildirim 2020) reported that EEG signals showed a great power for successful prediction. The difference may lie in the sample size or the content used. Another limitation among those papers is the lack of information on the sample size. Regarding the predicted output, eight papers provided sickness scores, with two papers using a sick/non-sick binary classification and eight proposing multiple sickness levels. Finally, each VR content used in those papers is shorter than recommended, with the shortest duration of nine seconds, a median of one minute, and a maximum of eleven minutes.

7.1 More features allow a better prediction

Generally, including a variety of factors and features could achieve high accuracy of prediction as in Jin et al. (2018), Porcino et al. (2020). Furthermore, providing scene movement solely with a significant sample size might also achieve a good result as in Islam et al. (2020), Lee et al. (2019). In contrast, prediction with a limited sample size tends to have reduced power as in Padmanaban et al. (2018), Wang et al. (2021). As we mentioned above, most of the papers included content features during data collection. Among those content features, scene movement, camera movement, and content type are the top three listed features (See Tables 6 and 7).

Table 6 Summary of papers on the prediction of cybersickness part 1.1

Source	Content factors	Interactive factors	Human factors	Hardware factors	Experimental factors	Performance
Dennison et al. (2016)	X	X	Type (HMD or display monitor)	X	X	78%
Hu et al. (2019)	Y (virtual camera movement (e.g., translational acceleration and rotational velocity) the composition of the virtual environment (e.g., scene depth))	X	X	X	X	Successfully reduced discomfort
Padmanaban et al. (2018)	Y (field of view, motion velocity, and stimulus depth)	X	X	X	X	Generally outperforms a naïve estimate, but limited by size of dataset
Lee et al. (2019)	Y(saliency, optical flow, and disparity maps of an input video, velocity, and depth)	X	X	X	X	Correlation (0.84)
Kim et al. (2020)	Y (VR Content , scene motion)	X	X	X	X	90%.
Kim et al. (2020)	Y (Scene themes, FOV presence, Camera Movement)	Controllability	Age and gender	X	X	86.2%
Islam et al. (2020)	Y (Scene movement)	X	X	X	X	97.4%
Jin et al. (2018)	Y (VR content motion, texture, color)	Y (Controllability)	Y (Video game experience, VR game experience, MSSQ)	Y (Hardware position and rotation)	X	R2 (0.868)
Agundez et al. (2019)	Y (Camera movement)	X	X	X	X	58% (Best result)
Anwar et al. (2020)	Y (content type (fast, medium, and slow)); camera motion (fixed, horizontal, and vertical); the number of moving targets (none, single, and multiple); Stailing	X	X	X	X	90%

Considering the variety of content features especially scene movement, is key to high accuracy, especially together with large sample size (Islam et al. 2020; Kim et al. 2018; Liao et al. 2020; Porcino et al. 2020). However, as aforementioned, there is a need for papers to clearly document the sample size for better comparison. Interestingly, Wang et al. did not consider any variety of factors in their paper. Instead, they utilized a deep long short term memory model to predict cybersickness with only a VR rollercoaster simulation game without changes (Wang et al. 2019). As a result, they achieved a Pearson correlation coefficient of .89 (Wang et al. 2019). Among the reviewed papers, Jin et al. (2018) and Porcino et al. (2020) considered all the categories of factors except experimental ones (Fig 3). For example, for training purposes, chosen factors in Jin's paper included hardware movement as a hardware factor (the changes of position and rotation of the head-mounted display (HMD)), motion, texture, and color as the content factors, video game experience, VR game experience and susceptibility to motion sickness as human factors (Jin et al. 2018). Meanwhile, Porcino's paper

Table 7 Summary of papers on the prediction of cybersickness Part 1.2

Source	Content factors	Interactive factors	Human factors	Hardware factors	Experimental factors	Performance
Wang et al. (2021)	X	X	Y(Age, Game experience, Ethnicity)	Y (HMD and CAVE)	X	Moderate correlation
Wang et al. (2019)	X	X	X	X	X	Correlation (0.89)
Chang et al. (2021)	Y (VR scene orientation)	X	X	X	Y (Controllability of user body)	explain 34.8% of the total variance in cybersickness
Recenti et al. (2021)	X	X	X	Y (Accompanied hardware platform)	X	74.7% (Random forest)
Liao et al. (2020)	Y (Scene difference)	X	Y (Gender)	X	X	38%/63%/87%(scene difference)
Porcino et al. (2020)	Y (Time Stamp; Speed; acceleration Rotation (x, y, and z); Position (x, y, and z); Region Of Interest; Size of FOV Frame Rate; Static Frame; DoF; Automatic Camera)	Y (Degree of Control, HMD type)	Y (Gender, Age, VR Experience, Flicker, Sensibility, Pre-symptoms, Glasses-wearing Vision Impairments, Posture instability, Dominant Eye)	Y (Haptic Feedback, Frame Rate)	X	best 99.0% for binary and 98.9% for quarterly
Kim et al. (2018)	Y (Object movement, camera movement, content component)	X	X	X	X	Correlation(0.72)

is probably the most comprehensive in factors and achieved the highest accuracy among all papers.

7.2 Individual susceptibility needs more attention

Six papers considered human factors for data collection. However, only three papers included human factors as inputs (Porcino et al. 2020; Wang et al. 2021; Jin et al. 2018). In addition, we cannot conclude that adding human factors as inputs increases the prediction accuracy due to the methodological variations among papers. It appears to be simple to have a binary or quarterly classification based on the output and customized thresholds that differed among studies. How to correctly determine the threshold is another problem needed to be discussed. For example, a person with a low FMS score at the beginning and a high FMS score at the end and a person with a medium FMS score all the time could have the same mean FMS score and be grouped into one cluster. There is a concern for more detailed standardized classification. Nevertheless, the addition of human factors could better answer the following questions: (1) What kinds of people tend to get sick? (2) Why does an individual reacts differently to different exposure? Or, what factor is an individual sensitive to? Unfortunately, the present review still fails to give answers to those questions. Therefore, we sincerely call for more high-quality research in the prediction field.

Tables 6, 7 summarize papers on the prediction of cybersickness with their associated factors and performance (either as an accuracy expressed in percentage or as a correlation with the subjective ratings, or with a text description if no numerical result is provided). Note that although the five factors (content, interaction, human, hardware, and experimental) describe the variety of VR experiences during the data collection stage, the inputs to the prediction model may not be equal to the included factors. Tables 8 and 9 summarize more methodological details with physiological and subjective measures, number of participants (NOP) recruited for data collection and NOP recruited for evaluation, sample size, inputs to the model, output of the model, and finally, the model used.

8 Suggestions for future studies

To conclude, our findings could provide several insights for future research, highlighted as follows:

– *Profiling individual susceptibility:* Characterizing cybersickness still remains a problem due to three main factors: (1) susceptibility variation among individuals, (2) the difficulty of measuring symptoms, and (3) content-dependent sensitivity. Hence, our suggestions are 1.

pre-screening the participants by basic demographics and individual susceptibility. It would require to develop and validate a cybersickness susceptibility questionnaire for screening the participants. Or directly through a VR game involving enough translational and rotational movement (e.g., a VR roller coaster). 2. Data analysis must be applied to characterize the features of sensitive individuals.

– *Potential of VR scene to induce cybersickness:* Researchers did many user studies with customized or commercial VR games, applications, or 360 videos. Until now, whether those VR experiences could induce a sufficient amount of cybersickness or not was mostly by researchers' experience or by pilot test during the design stage, which could be biased. Hence, we strongly suggest future studies to validate and standardize a method to evaluate the potential of VR scene to induce cybersickness . Furthermore, it could be interesting to use it together with the cybersickness susceptibility questionnaire to have a complete profile of human and content factors.

– *Standardize VR experiment database:* Develop a standardized database which provides passive (360 videos, Roller coasters) and active VR experiences (e.g., games), categorized by levels of content factors. We call for such a standardized database so as to enable comparison among studies.

– *Standardize VR design framework:* Develop a standardized framework that allows the manipulation of targeted content factors and control factors levels for different experimental purposes. The framework would at least contain standard navigation methods, different levels of navigation speed (both translational or rotational), and different controllability. Ideally, the same framework would be shared between studies, ensuring the comparison of results from different papers. GingerVR, developed by Ang and Quarries, provides a promising example for such a framework (Ang and Quarles 2020).

– *Measurement of cybersickness:* Based on the findings in our review, it lacks proper validated physiological measurement. Also, a more fitting variant of SSQ could be developed for cybersickness-oriented studies. Following the rules in (Bimberg et al. 2020), the levels of cybersickness are encoded with several necessary quantities: 1. the intensity of the symptom; 2. the rate of symptom onset or intensity increases, while the stimulus is presented; 3. the rate of symptom decay or intensity decreases after the stimulus is removed; 4. the percentage of users who experience the symptom at a fixed level or above. The standardized framework would collect those data with subjective questionnaires like SSQ, FSQ, and objective measures.

– *Exploration of sensory cues reweighting:* Sensory cues integration process during VR navigation is essential

Table 8 Summary of papers on the prediction of cybersickness part 2.1

Source of paper	Physiological measure	Subjective measure	NOP for data collection/evaluation	Sample size	Inputs	Outputs	Model
Dennison et al. (2016)	ECG, EGG, EOG, PPG, breathing rate, and GSR	FMS and post-SSQ	20(6f)/X	210000	Physiological signals, SSQ and FMS scores	Classification	Regression models
Hu et al. (2019)	X	Post-SSQ	22(9f)/28(10f)	NA	virtual camera movement (e.g., translational acceleration and rotational velocity) and the composition of the virtual environment (e.g., scene depth)	Sickness score	Self-defined model
Padmanaban et al. (2018)	X	Post-SSQ	96(20f)/X	NA	Speed of scene	Sickness score	Decision tree
Lee et al. (2019)	X	Post-SSQ,MSSQ-short	Existed Database/X	NA	Raw video frame image, optical flow map (for velocity feature), disparity map (for depth feature), saliency map (for eye movement feature).	NOT SPECIFIED (Level of cybersickness)	3D CNN
Kim et al. (2020)	X	Customized rating	21(NA)/X	NA	Motion feature and sickness score	Sickness score	Self-defined model
Kim et al. (2020)	X	Five-Point Likert scale rating	Existed Database/154(83f)	8008	VR content images and corresponding conflict maps	VIMS Score	BOS model(U-Net + ResNet 18)
Islam et al. (2020)	HR, GSR, breathing rate (BR), and HRV data	FMS Pre-post SSQ	31 (2f)/X	14774	The physiological signals labeled using FMS and FMS	Three classes(Low, Medium, High)	CNN-LSTM and SVM
Jin et al. (2018)	X	Rank-rating score; post-SSQ	24 (10f)/X	2400	VR content, head movement, individual characters	NOT SPECIFIED (Level of cybersickness)	CNN and LSTM-RNN and SVR

to shape the causality of cybersickness. Recently, though hardly accessible, the advanced biological measures like fMRI, PET imaging , EvestG could provide more opportunities to shed light on hidden conjunctions of factors.

– *Standardized process of measurements:* The measurements should cover the three stages of the experiment (before VR exposure, during VR exposure, and after VR exposure.) It helps to better understand the user adapta-

tion and recovery ability so as to further understand an individual susceptibility.

– *Mitigation techniques:* Currently, there is no absolute promising strategy to eliminate cybersickness, also no golden solution guaranteeing to minimize the cybersickness symptoms for each individual. Similarly, we would propose to profile the individual susceptibility with a multi-factorial rating and adjust the visual content or compensate the vestibular sensation accordingly.

Table 9 Summary of papers on the prediction of cybersickness part 2.2

Source of paper	Physiological measure	Subjective measure	NOP for data collection/evaluation	Sample size	Inputs	Outputs	Model
Garcia-Agundez et al. (2019)	ECG, GSR, BR, EOG	Pre-post SSQ	66(NA)/X	NA	The physiological signals and game movement	Binary classification	Decision trees and SVM and KNN
Shahid Anwar et al. (2020)	X	SSQ	40(15f)/X	NA	Content-type, Camera motion; the number of movies targets labeled with 3 SSQ levels	Cybersickness score	ANN
Wang et al. (2021)	X	Pre-post SSQ	244(NA)/X	244	Age, Game experience, Ethnicity; SSQ score	Not specified (Susceptibility of cybersickness)	Fuzzy logic
Wang et al. (2019)	Postural sway	Pre-post SSQ	11(4f)/X	2048	Postural sway signal	Sickness score	LSTM
Chang et al. (2021)	Eye-tracking	Pre-post SSQ	20 (NA)/X	NA	Eye-related measures (Fixation duration; Deviation from the center point; Distance between the eye gaze and the moving point)	SSQ total score	Linear Regression
Recenti et al. (2021)	EEG, HR, EMG	MSQ	28(22f)/X	83	EEG, HR, EMG and MSQ	Motion sickness index	RF, GB, ADA-B,SVM, KNN, and MLP
Liao et al. (2020)	EEG	SSQ	130(65f)/X	78000	EEG	Sickness index	LSTM
Porcino et al. (2020)	X	Pre-post VRSQ	35(9f)/X	18780	Features stated in content, interaction, hardware, and human factors	Binary classification/ Quarterly classification(none, slight, moderate, severe)	Trees
Kim et al. (2018)	X	Customized rating	80(NA)/X	NA	Features stated in content and subjective sickness score	Sickness score	Support vector regression

– *Prediction of cybersickness:* The individual susceptibility may vary a lot: one can be sensitive to content factor, while another could be sensitive to hardware factor. Or, one can be sensitive to only one specific factor, and another can be sensitive to multiple ones. Hence the prediction of cybersickness should include all facets of contributing factors (covering the five categories we proposed in this review). A larger sample size and an evaluation of the prediction is also a must. Furthermore, the classification of individual susceptibility could be more detailed to unlock the mystery of cybersickness. We presented an example in Fig. 4 based on our empirical experience. However, we strongly call for rigorous studies to define and standardize the thresholds and associated types as in Kennedy et al. (2003).

– *Increase the quality of research:* Finally, the general quality of papers should be enhanced with larger sample size, more precise reports on the methodology, and detailed analysis.

9 Conclusion

Despite the advances in hardware technologies, cybersickness remains an inevitable issue and poses challenges to the massive adoption of VR. The leading causes of cybersickness were extended to five categories as content, interaction, human, hardware, and experimental factors. The content and interaction factors are the most researched, with navigation (profiles or method) as the most widely investigated subfactor. Meanwhile, our review reveals an increasing interest in experimental factors. Comparatively, as the hardware advanced with modern technology, hardware-induced discomfort is now considered minimal but still needs attention on latency. However, hardware factors potentially impact the influence of content factors (for example, larger hardware FOV enables exposure to more peripheral visual contents.). Human factors have recently drawn more attention as well, with gender as the most researched sub-factor. Though researchers took the effort to identify a few predominant factors due to the multi-faceted characteristics of cybersickness and a great variety of included factors among studies, little can be concluded from the literature. The best way to solve cybersickness is to profile human susceptibility. Hence, it is suggested to establish a standardized process of
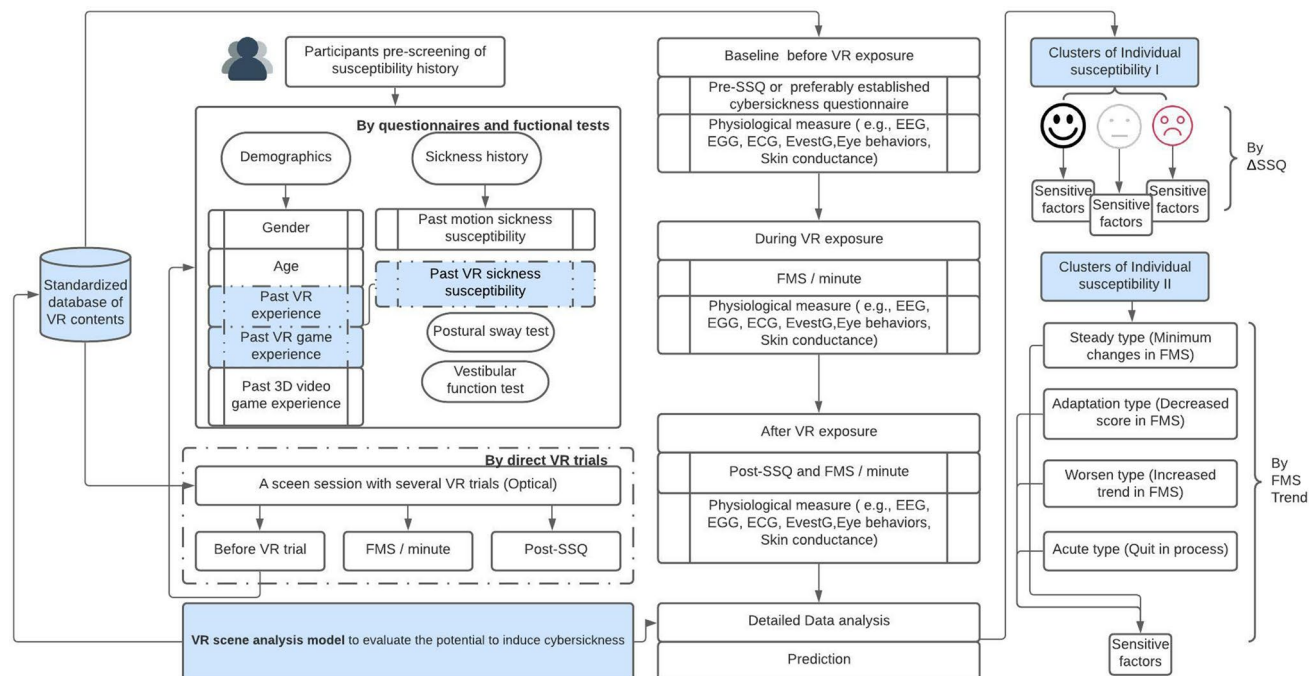

Fig. 4 Towards a potential standardized experiment protocol for studying individual susceptibility. We colored the boxes in light blue that needed standardization and validation. The boxes outlined with dotted lines potentially have a high indication for individual susceptibility before formal experiment. Finally, this diagram is just for suggestions and not without flaws. For example, the screening session could potentially have an impact on the following VR study. Hence, we suggest separating the screening session and future VR sessions with a minimum of seven days. We discuss each block in Sect. 8 for details

experimental settings to allow comparison and synthesis of the literature (Chang et al. 2020; Adhanom et al. 2021b). As mentioned above, the inclusion of pre-SSQ is a must. Also, the inclusion of both subjective and objective measures is highly recommended. As a complement, we also propose a pre-screening session to identify individual susceptibility before the formal experiment. This could benefit detailed profiling of cybersickness. Participants could be grouped into low, medium, and high susceptibility for further analysis. We also raise the attention on conducting a better-controlled experiment with a larger sample size when considering a factorial design. In addition, detailed descriptions of methodology are necessary, including demographics, hardware specifications, features of VR content, and interaction (especially a description of locomotion style, speed parameters, controllability, time or ratio in acceleration, etc.). Additionally, of particular interest is the reporting of high susceptibility researchers on their own experience of cybersickness (Zielasko 2021). Although limited to a single individual, the detailed recollection provided in Zielasko's paper can certainly inspire other researchers towards identifying the pattern of high susceptibility to cybersickness.

Overall, there is a pressing need for modeling users' susceptibility with more data analysis around human factors. Figure 4 summarizes such a potential standardized experiment protocol to explore individual susceptibility.

References

Abdul Jabbar AI, Felicia P (2015) Gameplay engagement and learning in game-based learning: a systematic review. Rev Educ Res 85(4):740–779

Adhanom IB, Al-Zayer M, Macneilage P, Folmer E (2021) Field-of-view restriction to reduce vr sickness does not impede spatial learning in women. ACM Trans Appl Percept 18(2):5. https://doi.org/10.1145/3448304

Adhanom IB, Griffin NN, MacNeilage P, Folmer E (2020) The effect of a foveated field-of-view restrictor on vr sickness. In: 2020 IEEE conference on virtual reality and 3D user interfaces (VR), pp 645–652. IEEE

Adhanom IB, Al-Zayer M, Macneilage P, Folmer E (2021) Field-of-view restriction to reduce VR sickness does not impede spatial learning in women. ACM Trans Appl Percept 18(2):6

Adhanom IB, Al-Zayer M, Macneilage P, Folmer E (2021) Field-of-view restriction to reduce vr sickness does not impede spatial learning in women. ACM Trans Appl Percept 18:6

Agić A, Murseli E, Mandić L, Skorin-Kapov L (2020) The impact of different navigation speeds on cybersickness and stress level in vr. J Graph Eng Des 11(1):5

Al Zayer M, MacNeilage P, Folmer E (2018) Virtual locomotion: a survey. IEEE Trans. Vis Comput Graph 26(6):2315–2334

Al Zayer M, Adhanom IB, MacNeilage P, Folmer E (2019) The effect of field-of-view restriction on sex bias in vr sickness and spatial navigation performance. In: Proceedings of the 2019 CHI conference on human factors in computing systems, CHI '19, pp 354:1–354:12, New York, NY, USA, ACM

Al Zayer M, Adhanom IB, MacNeilage P, Folmer E (2019) The effect of field-of-view restriction on sex bias in vr sickness and spatial navigation performance. In: Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–12

Al Zayer M, MacNeilage P, Folmer E (2018) Virtual locomotion: a survey. IEEE Trans Vis Comput Graph, pp 1–1, 12

Aldaba CN, White PJ, Byagowi A, Moussavi Z (2017) Virtual reality body motion induced navigational controllers and their effects on simulator sickness and pathfinding. In: 2017 39th annual international conference of the IEEE engineering in medicine and biology society (EMBC), pp 4175–4178. IEEE

Aldaba CN, Moussavi Z (2020) Effects of virtual reality technology locomotive multi-sensory motion stimuli on a user simulator sickness and controller intuitiveness during a navigation task. Med Biol Eng Comput 58(1):143–154

Alexandrovsky D, Putze S, Bonfert M, öffner SH, Michelmann P, Wenig D, Malaka R, Smeddinck JD (2020) Examining design choices of questionnaires in vr user studies. pp 1–21

Almeida A, Rebelo F, Noriega P, Vilar E (2017) Virtual reality self induced cybersickness: an exploratory study. In: International conference on applied human factors and ergonomics, pp 26–33. Springer

Ames SL, Wolffsohn JS, Mcbrien NA (2005) The development of a symptom questionnaire for assessing virtual reality viewing using a head-mounted display. Optom Vis Sci 82(3):168–176

Ang S, Quarles J (2020) Gingervr: an open source repository of cybersickness reduction techniques for unity. pp 460–463

Aoyama K, Iizuka H, Ando H, Maeda T (2015) Four-pole galvanic vestibular stimulation causes body sway about three axes. Sci Rep 5:10168

Arafat IM, Ferdous SM, Quarles J (2018) Cybersickness-provoking virtual reality alters brain signals of persons with multiple sclerosis. In: 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp 1–120. IEEE

Ashiri M, Lithgow B, Suleiman A, Moussavi Z, Mansouri B (2019) Visio-vestibular interaction in humans: changes in the vestibular response following visual stimuli of different colors. J Med Biol Eng 39(2):238–243

Ashiri M, Lithgow B, Suleiman A, Blakley B, Mansouri B, Moussavi Z (2020) Differences between physical vs virtual evoked vestibular responses. Ann Biomed Eng 48(4):1241–1255

Ashiri M, Lithgow B, Suleiman A, Mansouri B, Moussavi Z (2020) Quantitative measures of the visually evoked sensation of body movement in space (Vection) using Electrovestibulography (EVestG). Virtual Real 25(3):731–744

Ashiri M, Lithgow B, Suleiman A, Mansouri B, Moussavi Z (2021) Quantitative measures of the visually evoked sensation of body movement in space (vection) using electrovestibulography (evestg). Virtual Real 25(3):731–744

Ashiri M, Lithgow B, Mansouri B, Moussavi Z (2020) Comparison between vestibular responses to a physical and virtual reality rotating chair. In: Proceedings of the 11th augmented human international conference, pp 1–4

Ashton MC, Lee K, Perugini M, Szarota P, De Vries RE, Di Blas L, Boies K, De Raad B (2004) A six-factor structure of personality-descriptive adjectives: solutions from psycholexical studies in seven languages. J Pers Soc Psychol 86(2):356

Bala P, Oakley I, Nisi V, Nunes NJ (2021) Dynamic field of view restriction in 360° video: Aligning optical flow and visual slam to mitigate vims. In Proceedings of the 2021 CHI conference on human factors in computing systems, pp 1–18. https://doi.org/10.1145/3411764.3445499

Bimberg P, Weissker T, Kulik A (2020) On the usage of the simulator sickness questionnaire for virtual reality research. In: 2020 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops (VRW), pp 464–467. IEEE

Bouchard S, Robillard G, Renaud P (2007) Revising the factor structure of the simulator sickness questionnaire. Annu Rev Cyberther Telemed 5(Summer):128–137

Brown DJ, Pastras CJ, Curthoys IS (2017) Electrophysiological measurements of peripheral vestibular function-a review of electrovestibulography. Front Syst Neurosci 11:34

Brument H, Marchal M, Olivier AH, Argelaguet F (2020) Influence of dynamic field of view restrictions on rotation gain perception in virtual environments. In: Proceedings of the international conference on virtual reality and augmented reality, pp 20–40. Springer, Cham. https://doi.org/10.1007/978-3-030-62655-6_2

Cao Z, Jerald J, Kopper R (2018) Visually-induced motion sickness reduction via static and dynamic rest frames. In: 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp 105–112. IEEE

Caserman P, Garcia-Agundez A, Konrad R, Göbel S, Steinmetz R (2019) Real-time body tracking in virtual reality using a vive tracker. Virtual Real 23(2):155–168

Caserman P, Garcia-Agundez A, Gámez Zerban A, Göbel S (2021) Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Real

Caserman P, Garcia-Agundez A, Zerban AG, Göbel S (2021) Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Real

Chang E, Seo D, Kim HT, Yoo B (2018) An integrated model of cybersickness: understanding user's discomfort in virtual reality. J KIISE 45(3):251–279

Chang E, Kim HT, Yoo B (2020) Virtual reality sickness: a review of causes and measurements. Int J Hum Comput Interact 36(17):1658–1682

Chang E, Kim HT, Yoo B (2021) Predicting cybersickness based on user's gaze behaviors in hmd-based virtual reality. J Comput Des Eng 8(2):728–739

Chattha UA, Janjua UI, Anwar F, Madni TM, Cheema MF, Janjua SI (2020) Motion sickness in virtual reality: an empirical evaluation. IEEE Access 8:130486–130499

Chen CY, Chuang CH, Tsai TL, Chen HW, Wu PJ (2021) Reducing cybersickness by implementing texture blur in the virtual reality content. Virtual Real, pp 1–12

Cheung B, Vaitkus P (1998) Perspectives of electrogastrography and motion sickness. Brain Res Bull 47(5):421–431

Christou CG, Aristidou P (2017) Steering versus teleport locomotion for head mounted displays. In: International conference on augmented reality, virtual reality and computer graphics, pp 431–446. Springer

Clifton J, Palmisano S (2020) Effects of steering locomotion and teleporting on cybersickness and presence in hmd-based virtual reality. Virtual Real 24(3):453–468

Clifton J, Palmisano S (2019) Comfortable locomotion in vr: teleportation is not a complete solution. In: 25th ACM symposium on virtual reality software and technology, pp 1–2

Coomer N, Bullard S, Clinton W, Williams-Sanders B (2018) Evaluating the effects of four vr locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In: Proceedings of the 15th ACM symposium on applied perception, pp 1–8

Cortes CAT, Chen HT, Lin CT (2019) Analysis of vr sickness and gait parameters during non-isometric virtual walking with large translational gain. In: 25th ACM symposium on virtual reality software and technology, pp 1–2

Curry C, Li R, Peterson N, Stoffregen TA (2020) Cybersickness in virtual reality head-mounted displays: examining the influence of sex differences and vehicle control. Int J Hum Comput Interact, pp 1–7

Davis S, Nesbitt K, Nalivaiko E (2014) A systematic review of cybersickness. In: Proceedings of the 2014 conference on interactive entertainment, pp 1–9

Davis S, Nesbitt K, Nalivaiko E (2015) Comparing the onset of cybersickness using the oculus rift and two virtual roller coasters. In: Proceedings of the 11th australasian conference on interactive entertainment (IE 2015), 27, pp 30

Del Cid DA, Larranaga D, Leitao M, Mosher RL, Berzenski SR, Gandhi V, Drew SA (2021) Exploratory factor analysis and validity of the virtual reality symptom questionnaire and computer use survey. Ergonomics 64(1):69–77

Dennison MS, D'Zmura M (2017) Cybersickness without the wobble: experimental results speak against postural instability theory. Appl Ergon 58:215–223

Dennison M, D'Zmura M (2018) Effects of unexpected visual motion on postural sway and motion sickness. Appl Ergon 71:9–16

Dennison MS, Wisti AZ, D'Zmura M (2016) Use of physiological signals to predict cybersickness. Displays 44:42–52

Dużmańska N, Strojny P, Strojny A (2018) Can simulator sickness be avoided? a review on temporal aspects of simulator sickness. Front Psychol 9:2132

Elwardy M, Zepernick HJ, Hu Y, Chu TMC, Sundstedt V (2020) 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

Farmani Y, Teather RJ (2018) Viewpoint snapping to reduce cybersickness in virtual reality. In: Proceedings of the 44th graphics interface conference, pp 168–175. Canadian Human-Computer Communications Society

Farmani Y, Teather RJ (2020) Evaluating discrete viewpoint control to reduce cybersickness in virtual reality. Virtual Real, pp 1–20

Fernandes AS, Feiner SK (2016) Combating vr sickness through subtle dynamic field-of-view modification. In 2016 IEEE symposium on 3D user interfaces (3DUI), pp 201–210. IEEE

Freiwald JP, Göbel Y, Mostajeran F, Steinicke F (2020) The cybersickness susceptibility questionnaire: predicting virtual reality tolerance. In: Proceedings of the conference on mensch und computer, pp 115–118. https://doi.org/10.1145/3404983.3410022

Frommel J, Sonntag S, Weber M (2017) Effects of controller-based locomotion on player experience in a virtual reality exploration game. In: Proceedings of the 12th international conference on the foundations of digital games, pp 1–6

Fulvio JM, Ji M, Rokers B (2021) Variations in visual sensitivity predict motion sickness in virtual reality. Entertain Comput 38:5

Gallagher M, Ferrè ER (2018) Cybersickness: a multisensory integration perspective. Multisens Res 31(7):645–674

Gallagher M, Choi R, Ferrè ER (2020) Multisensory interactions in virtual reality: optic flow reduces vestibular sensitivity, but only for congruent planes of motion. Multisens Res 33(6):625–644. https://doi.org/10.1163/22134808-20201487

Garcia-Agundez A, Reuter C, Becker H, Konrad R, Caserman P, Miede A, Göbel S (2019) Development of a classifier to determine factors causing cybersickness in virtual reality environments. Games Health J 8(6):439–444

Garcia-Agundez A, Reuter C, Caserman P, Konrad R, Göbel S (2019) Identifying cybersickness through heart rate variability alterations. Int J Virtual Real 19(1):1–10

Gardé A, Léger PM, Sénécal S, Fredette M, Labonté-Lemoyne E, Courtemanche F, and Ménard JF (2018) The effects of a vibro-kinetic multi-sensory experience in passive seated vehicular movement in a virtual reality context. In: Extended abstracts of the 2018 CHI conference on human factors in computing systems, pp 1–6

Gavgani AM, Hodgson DM, Nalivaiko E (2017) Effects of visual flow direction on signs and symptoms of cybersickness. PloS one 12(8). https://doi.org/10.1371/journal.pone.0182790

Gavgani AM, Nesbitt KV, Blackmore KL, Nalivaiko E (2017) Profiling subjective symptoms and autonomic changes associated with cybersickness. Auton Neurosci 203:41–50

Geršak G, Lu H, Guna J (2020) Effect of vr technology matureness on vr sickness. Multimed Tools Appl 79(21):14491–14507

Gilbert SB, Jasper A, Sepich NC, Doty TA, Kelly JW, Dorneich MC (2021) Individual differences task attention in cybersickness: a call for a standardized approach to data sharing. In: Proceedings - 2021 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops, VRW 2021, pp 161–164, 3

Gonçalves G, Melo M, Bessa M (2018) Virtual reality games: a study about the level of interaction vs. narrative and the gender in presence and cybersickness. In: 2018 international conference on graphics and interaction (ICGI), pp 1–8. IEEE

Grassini S, Laumann K, Luzi AK (2021) Association of individual factors with simulator sickness and sense of presence in virtual reality mediated by head-mounted displays (hmds). Multimodal Technol Interact 5(3):7

Grassini S, Laumann K (2020) Are modern head-mounted displays sexist? a systematic review on gender differences in hmd-mediated virtual reality. Front Psychol 11. https://doi.org/10.3389/fpsyg.2020.01604

Greenlee MW, Frank SM, Kaliuzhna M, Blanke O, Bremmer F, Churan J, Cuturi LF, MacNeilage PR, Smith AT (2016) Multisensory integration in self motion perception. Multisens Res 29(6–7):525–556

Gruden T, Popović NB, Stojmenova K, Jakus G, Miljković N, Tomažič S, Sodnik J (2021) Electrogastrography in autonomous vehicles-an objective method for assessment of motion sickness in simulated driving environments. Sensors (Switzerland) 21(2):1–20

Guna J, Geršak G, Humar I, Song J, Drnovšek J, Pogačnik M (2019b) Influence of video content type on users' virtual reality sickness perception and physiological response. Futur Gener Comput Syst 91:263–276

Guna J, Geršak G, Humar I, Krebl M, Orel M, Lu H, Pogačnik M (2020) Virtual reality sickness and challenges behind different technology and content settings. Mob Netw Appl 25(4):1436–1445. https://doi.org/10.1007/s11036-019-01373-w

Habgood MJ, Moore D, Wilson D, Alapont S (2018) Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. In: Proceedings of the 2018 IEEE conference on virtual reality and 3d user interfaces (VR), IEEE, pp 371–378. https://doi.org/10.1109/VR.2018.8446130

Häkkinen J, Ohta F, Kawai T (2019) Time course of sickness symptoms with hmd viewing of 360-degree videos. Electron Imag 2019(3):60403

Hansen JP, Trudslev AK, Harild SA, Alapetite A, Minakata K (2019) Providing access to vr through a wheelchair. In: Extended Abstracts of the 2019 CHI conference on human factors in computing systems, pp 1–8

Harada T, Sugawara T, Ito T, Wada Y, Fukunaga M, Sadato N, Larroque SK, Demertzi A, Laureys S, Sakai H (2021) Vestibular morphological asymmetry associated with motion sickness susceptibility. Front Neurosci 15:763040. https://doi.org/10.3389/fnins.2021.763040

Heo J, Yoon G (2020) EEG studies on physical discomforts induced by virtual reality gaming. J Electr Eng Technol 15(3):1323–1329. https://doi.org/10.1007/s42835-020-00373-1

Hildebrandt J, Schmitz P, Valdez AC, Kobbelt L, Ziefle M (2018) Get well soon! human factors' influence on cybersickness after redirected walking exposure in virtual reality. In: International conference on virtual, augmented and mixed reality, pp 82–101. Springer

Hopper JE, Finney H, Jones JA (2019) Field of view and forward motion discrimination in virtual reality. In 2019 IEEE conference on virtual reality and 3D user interfaces (VR), pp 1663–1666. IEEE

Howard MC, Van Zandt EC (2021) A meta-analysis of the virtual reality problem: unequal effects of virtual reality sickness across individual differences. Virtual Real 1(1–26):5

Hsiao CY, Liu YA, Wang MJ (2019) Evaluation of suitable rest times for the use of optical head-mounted displays. In: International conference on applied human factors and ergonomics, pp 34–42. Springer

Hu P, Sun Q, Didyk P, Wei L-Y, Kaufman AE (2019) Reducing simulator sickness with perceptual camera control. ACM Trans Graph (TOG) 38(6):1–12

Hu Y, Elwardy M, Zepernick HJ (2021) On the effect of standing and seated viewing of 360o videos on subjective quality assessment: A pilot study. Computers 10(6):6

Hunt X, Potter L. E. (2018) High computer gaming experience may cause higher virtual reality sickness. In: Proceedings of the 30th australian conference on computer-human interaction, pp 598–601

Hussain R, Chessa M, Solari F (2021) Mitigating cybersickness in virtual reality systems through foveated depth-of-field blur. Sensors 21:6. https://doi.org/10.3390/s21124006

Huygelier H, Schraepen B, van Ee R, Abeele VV, Gillebert CR (2019) Acceptance of immersive head-mounted virtual reality in older adults. Sci Rep 9(1):1–12

Hwang AD, Deng H, Gao Z, Peli E (2018) Quantifying visually induced motion sickness (vims) during stereoscopic 3d viewing using temporal vims rating. Electron Imag 2018(14):1–9

Iskenderova A, Weidner F, Broll W (2017) Drunk virtual reality gaming: exploring the influence of alcohol on cybersickness. In: Proceedings of the annual symposium on computer-human interaction in play, pp 561–572

Islam R, Lee Y, Jaloli M, Muhammad I, Zhu D, Rad P, Huang Y, Quarles J (2020) Automatic Detection and Prediction of Cybersickness Severity using Deep Neural Networks from user's Physiological Signals. In: Proceedings - 2020 IEEE international symposium on mixed and augmented reality, ISMAR 2020, pp 400–411, 11

Jeong D, Yoo S, Yun J (2019) Cybersickness analysis with eeg using deep learning algorithms. In: 2019 IEEE conference on virtual reality and 3D user interfaces (VR), pp 827–835. IEEE

Jin W, Fan J, Gromala D, Pasquier P (2018) Automatic prediction of cybersickness for virtual reality games. In: 2018 IEEE games, entertainment, media conference (GEM), pp 1–9. IEEE

Jung S, Li R, McKee R, Whitton MC, Lindeman RW (2021) Floor-vibration vr: mitigating cybersickness using whole-body tactile

stimuli in highly realistic vehicle driving experiences. IEEE Trans Vis Comput Graph 27(5):2669–2680

Kala N, Lim K, Won K, Lee J, Lee T, Kim S, Choe W (2017) P-218: An approach to reduce vr sickness by content based field of view processing. In: SID symposium digest of technical papers, 48:1645–1648, 5

Kala N, Lim K, Won K, Lee J, Lee T, Kim S, Choe W (2017) P-218: An approach to reduce vr sickness by content based field of view processing. In: SID symposium digest of technical papers, volume 48, pp 1645–1648. Wiley Online Library

Käser DP, Parker E, Glazier A, Podwal M, Seegmiller M, Wang CP, Karlsson P, Ashkenazi N, Kim J, Le A, et al. (2017) The making of google earth vr. In: ACM SIGGRAPH 2017 Talks, pp 1–2

Katsigiannis S, Willis R, Ramzan N (2018) A qoe and simulator sickness evaluation of a smart-exercise-bike virtual reality system via user feedback and physiological signals. IEEE Trans Cons Electron 65(1):119–127

Kaufeld M, Alexander T (2019) The impact of motion on individual simulator sickness in a moving base vr simulator with head-mounted display (hmd). In: International conference on human-computer interaction, pp 461–472. Springer

Kennedy RS, Drexler JM, Compton DE, Stanney KM, Lanham DS, Harm DL (2003) Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: Similarities and differences. Virtual and adaptive environments: Applications, implications, and human performance issues, p 247

Kennedy RS, Frank LH (1985) A review of motion sickness with special reference to simulator sickness. CANYON Research Group Inc., Westlake Village CA, Technical report

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psychol 3(3):203–220

Keshavarz B, Golding JF (2022) Motion sickness: current concepts and management. Curr Opin Neurol 35(1):107–112

Keshavarz B, Hecht H (2011) Axis rotation and visually induced motion sickness: the role of combined roll, pitch, and yaw motion. Aviat Space Environ Med 82(11):1023–1029

Keshavarz B, Hecht H (2011) Validating an efficient method to quantify motion sickness. Hum Factors 53(4):415–426

Keshavarz B, Hecht H (2014) Pleasant music as a countermeasure against visually induced motion sickness. Appl Ergon 45(3):521–527

Keshavarz B, Murovec B, Mohanathas N, Golding JF (2021) The visually induced motion sickness susceptibility questionnaire (vimssq): estimating individual susceptibility to motion sickness-like symptoms when using visual devices. Hum Factors. https://doi.org/10.1177/00187208211008687

Keshavarz B, Murovec B, Mohanathas N, Golding JF (2021) The visually induced motion sickness susceptibility questionnaire (vimssq): Estimating individual susceptibility to motion sickness-like symptoms when using visual devices. Hum Factors. https://doi.org/10.1177/00187208211008687

Khoirunnisaa AZ, Pane ES, Wibawa AD, Purnomo MH (2018) Channel selection of eeg-based cybersickness recognition during playing video game using correlation feature selection (cfs). In: 2018 2nd international conference on biomedical engineering (IBIOMED), pp 48–53. IEEE

Kim HG, Baddar WJ, Lim HT, Jeong H, Ro YM (2017) Measurement of exceptional motion in vr video contents for vr sickness assessment using deep convolutional autoencoder. In: Proceedings of the 23rd ACM symposium on virtual reality software and technology, pp 1–7

Kim J, Curthoys IS (2004) Responses of primary vestibular neurons to galvanic vestibular stimulation (gvs) in the anaesthetised guinea pig. Brain Res Bull 64(3):265–271

Kim N-G, Kim B-S (2019) The effect of retinal eccentricity on visually induced motion sickness and postural control. Appl Sci 9(9):1919

Kim J, Park T (2020) The onset threshold of cybersickness in constant and accelerating optical flow. Appl Sci 10(21):7808

Kim YY, Kim HJ, Kim EN, Ko HD, Kim HT (2005) Characteristic changes in the physiological components of cybersickness. Psychophysiology 42(5):616–625

Kim HK, Park J, Choi Y, Choe M (2018) Virtual reality sickness questionnaire (vrsq): motion sickness measurement index in a virtual reality environment. Appl Ergon 69:66–73

Kim S, Lee S, Kala N, Lee J, Choe W (2018) An effective fov restriction approach to mitigate vr sickness on mobile devices. J Soc Inf Dis 26(6):376–384

Kim W, Lee S, Bovik AC (2020) Vr sickness versus vr presence: a statistical prediction model. IEEE Trans Image Process 30:559–571

Kim S, Lee S, Ro YM (2020) Estimating vr sickness caused by camera shake in vr videography. In: Proceedings—international conference on image processing, ICIP, 2020-October:3433–3437, 10

Kim J, Oh H, Kim W, Choi S, Son W, Lee S (2020) A deep motion sickness predictor induced by visual stimuli in virtual reality. IEEE Trans Neural Netw Learn Syst. https://doi.org/10.1109/TNNLS.2020.3028080

Koch KL (2014) Gastric dysrhythmias: a potential objective measure of nausea. Exp Brain Res 232(8):2553–2561

Krokos E, Varshney A (2021) Quantifying VR cybersickness using EEG. Virtual Real 1–13. https://doi.org/10.1007/s10055-021-00517-2

Kuosmanen T (2019) The effect of visual detail on cybersickness: Predicting symptom severity using spatial velocity

LaViola JJ Jr (2000) A discussion of cybersickness in virtual environments. ACM Sigchi Bull 32(1):47–56

Lee JY, Han PH, Tsai L, Peng RD, Chen YS, Chen KW, Hung YP (2017) Estimating the Simulator Sickness in Immersive Virtual Reality with Optical Flow Analysis. SIGGRAPH Asia 2017 Posters, SA 2017, 11

Lee J, Kim M, Kim J (2017) A study on immersion and vr sickness in walking interaction for immersive virtual reality applications. Symmetry 9(5):78

Lee TM, Yoon J-C, Lee I-K (2019) Motion sickness prediction in stereoscopic videos using 3d convolutional neural networks. IEEE Trans Vis Comput Graph 25(5):1919–1927

Li X, Zhu C, Xu C, Zhu J, Li Y, Wu S (2020) Vr motion sickness recognition by using eeg rhythm energy ratio based on wavelet packet transform. Comput Methods Progr Biomed 188:105266

Liao C-Y, Tai S-K, Chen R-C, Hendry H (2020) Using eeg and deep learning to predict motion sickness under wearing a virtual reality device. IEEE Access 8:126784–126796

Lim K, Lee J, Won K, Kala N, Lee T (2020) A novel method for vr sickness reduction based on dynamic field of view processing. Virtual Real 25:331–340

Lim HK, Ji K, Woo YS, Han D-U, Lee D-H, Nam SG, Jang K-M (2021) Test-retest reliability of the virtual reality sickness evaluation using electroencephalography (eeg). Neurosci Lett 743. https://doi.org/10.1016/j.neulet.2020.135589

Lin JW, Duh HB, Parker DE, Abi-Rached H, Furness TA (2002) Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In: Proceedings ieee virtual reality, pp 164–171. IEEE

Litleskare S (2021) The relationship between postural stability and cybersickness: it's complicated—an experimental trial assessing practical implications of cybersickness etiology. Physiol Behav 236:7. https://doi.org/10.1016/j.physbeh.2021.113422

Lo W, So RH (2001) Cybersickness in the presence of scene rotational movements along different axes. Appl Ergono 32(1):1–14

Lopes P, Boulic R (2020) Towards designing games for experimental protocols investigating human-based phenomena. In:

Proceedings of the international conference on the foundations of digital games, pp 1–11. https://doi.org/10.1145/3402942.3403012

Lopes P, Tian N, Boulic R (2020a) Exploring blink-rate behaviors for cybersickness detection in vr. In 2020 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops (VRW), pp 795–796. IEEE

Lopes P, Tian N, Boulic R (2020b) Eye thought you were sick! Exploring eye behaviors for cybersickness detection in VR. In: Motion, interaction and games (MIG '20). Association for Computing Machinery, New York, NY, USA, Article 3, 1–10. https://doi.org/10.1145/3424636.3426906

Luks R, Liarokapis F (2019) Investigating motion sickness techniques for immersive virtual environments. In: Proceedings of the 12th ACM international conference on pervasive technologies related to assistive environments, pp 280–288. https://doi.org/10.1145/3316782.3321535

MacArthur C, Grinberg A, Harley D, Hancock M (2021) You're making me sick: A systematic review of how virtual reality research considers gender and cybersickness. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp 1–15

Magaki T, Vallance M (2019) Developing an accessible evaluation method of vr cybersickness. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 1072–1073. IEEE

Marengo J, Lopes P, Boulic R (2019) On the influence of the supine posture on simulation sickness in virtual reality. In 2019 IEEE Conference on Games (CoG), pp 1–8. IEEE

Martirosov S, Kopecek P (2017) Cyber sickness in virtual reality-literature review. Annals of DAAAM and Proceedings, 28. https://doi.org/10.2507/28th.daaam.proceedings.101

Matsuura Y, Takada H (2018) Comparison of electrogastrograms in a seated posture with those in a supine posture using wayland algorithm. In 2018 13th International Conference on Computer Science and Education (ICCSE), pp 1–5. IEEE

Mayor J, Raya L, Sanchez A (2019) A comparative study of virtual reality methods of interaction and locomotion based on presence, cybersickness and usability. IEEE Trans Emerg Topics Comput. https://doi.org/10.1109/TETC.2019.2915287

McGill M, Ng A, Brewster S (2017) 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

McHugh N (2019) Measuring and minimizing cybersickness in virtual reality

Melo MC, Raposo JV, Coelho A, Narciso DG, Bessa M (2019) Immersive 360° video user experience: impact of different variables in the sense of presence and cybersickness. https://doi.org/10.1007/s10209-017-0581-5

Melo M, Vasconcelos-Raposo J, Bessa M (2018) Presence and cybersickness in immersive content: effects of content type, exposure time and gender. Comput Graph 71:159–165

Mittelstaedt J, Wacker J, Stelling D (2018) Effects of display type and motion control on cybersickness in a virtual bike simulator. Displays 51:43–50

Moghadam K, Banigan C, Ragan E (2018) Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. IEEE Trans Vis Comput Graph, pp 1–1, 11

Moher D, Liberati A, Tetzlaff J, Altman DG, Group P et al (2009) Preferred reporting items for systematic reviews and meta-analyses: the prisma statement. PLoS Med 151(4):264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Monteiro P, Carvalho D, Melo M, Branco F, Bessa M (2018) Application of the steering law to virtual reality walking navigation interfaces. Comput Graph 77:80–87

Murray MM, Wallace MT (2011) The neural bases of multisensory processes. CRC Press

Nalivaiko E, Davis SL, Blackmore KL, Vakulin A, Nesbitt KV (2015) Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time. Physiol Behav 151:583–590

Napadow V, Sheehan JD, Kim J, LaCount LT, Park K, Kaptchuk TJ, Rosen BR, Kuo B (2013) The brain circuitry underlying the temporal evolution of nausea in humans. Cerebral cortex 23(4):806–813

Naqvi SAA, Badruddin N, Jatoi MA, Malik AS, Hazabbah W, Abdullah B (2015) Eeg based time and frequency dynamics analysis of visually induced motion sickness (vims). Australas Phys Eng Sci Med 38(4):721–729

Narciso D, Bessa M, Melo M, Vasconcelos-Raposo J (2019) Virtual reality for training-the impact of smell on presence, cybersickness, fatigue, stress and knowledge transfer. In 2019 International Conference on Graphics and Interaction (ICGI), pp 115–121. IEEE

Ng AK, Chan LK, Lau HY (2020) A study of cybersickness and sensory conflict theory using a motion-coupled virtual reality system. Displays 61:101922. https://doi.org/10.1016/j.displa.2019.08.004

Nie GY, Duh HBL, Liu Y, Wang Y (2019) Analysis on mitigation of visually induced motion sickness by applying dynamical blurring on a user's retina. IEEE Trans Visual Comput Graph. https://doi.org/10.1109/TVCG.2019.2893668

Nilsson NC, Serafin S, Steinicke F, Nordahl R (2018) Natural walking in virtual reality: a review. Comput Entertain (CIE) 16(2):1–22

Niu Y, Wang D, Wang Z, Sun F, Yue K, Zheng N (2020) User experience evaluation in virtual reality based on subjective feelings and physiological signals. Electron Imaging 2020(13):60413-1. https://doi.org/10.2352/J.ImagingSci.Technol.2019.63.6.060413

Norouzi N, Bruder G, Welch G (2018) Assessing vignetting as a means to reduce vr sickness during amplified head rotations. In: Proceedings of the 15th ACM Symposium on Applied Perception, pp 1–8

Oman CM (1991) Sensory conflict in motion sickness: an observer theory approach. Pictorial communication in virtual and real environments, 362–376

Padmanaban N, Ruban T, Sitzmann V, Norcia AM, Wetzstein G (2018) Towards a machine-learning approach for sickness prediction in 360 stereoscopic videos. IEEE Trans Vis Comput Graph 24(4):1594–1603

Palmisano S, Mursic R, Kim J (2017) Vection and cybersickness generated by head-and-display motion in the oculus rift. Displays 46:1–8

Palmisano S, Allison RS, Kim J (2020) Cybersickness in head-mounted displays is caused by differences in the user's virtual and physical head pose. Front Virt Real 1:24

Pane ES, Khoirunnisaa AZ, Wibawa AD, Purnomo MH (2018) Identifying severity level of cybersickness from eeg signals using cn2 rule induction algorithm. In 2018 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS), volume 3, pp 170–176. IEEE

Patterson R, Winterbottom MD, Pierce BJ (2006) Perceptual issues in the use of head-mounted visual displays. Hum Factors 48(3):555–573

Peck TC, Sockol LE, Hancock SM (2020) Mind the gap: the underrepresentation of female participants and authors in virtual reality research. IEEE Trans Vis Comput Graph 26(5):1945–1954

Pöhlmann KMT, Föcker J, Dickinson P, Parke A, O'Hare L (2021) The effect of motion direction and eccentricity on vection, VR sickness and head movements in virtual reality. Multisens Res 340(3):1–40

Porcino T, Rodrigues EO, Silva A, Clua E, Trevisan D (2020) Using the gameplay and user data to predict and identify causes of cybersickness manifestation in virtual reality games. In 2020 IEEE 8th international conference on serious games and applications for health (SeGAH), pp 1–8. IEEE

Porter III J, Robb A (2019) An analysis of longitudinal trends in consumer thoughts on presence and simulator sickness in vr games, pp 277–285. https://doi.org/10.1145/3311350.3347159

Rangelova S, Rehm K, Diefenbach S, Motus D, André E (2020) Gender differences in simulation sickness in static vs. moving platform vr automated driving simulation. In: International conference on human-computer interaction, pp 146–165. Springer

Rebenitsch L, Owen C (2016) Review on cybersickness in applications and visual displays. Virtual Real 20(2):101–125

Rebenitsch L, Owen C (2021) Estimating cybersickness from virtual reality applications. Virtual Real 25:165–174

Rebenitsch L, Owen C (2014) Individual variation in susceptibility to cybersickness. In: Proceedings of the 27th annual ACM symposium on User interface software and technology, pp 309–317

Rebenitsch L, Quinby B (2019) Cybersickness and postural sway using hmd orientation. In: International conference on human-computer interaction, pp 500–509. Springer

Recenti M, Ricciardi C, Aubonnet R, Picone I, Jacob D, Svansson HÁR, Agnarsdóttir S, Karlsson GH, Baeringsdóttir V, Petersen H, Gargiulo P (2021) Toward predicting motion sickness using virtual reality and a moving platform assessing brain, muscles, and heart signals. Front Bioeng Biotechnol 9:635661. https://doi.org/10.3389/fbioe.2021.635661

Ren D, Goldschwendt T, Chang Y, Höllerer T (2016) Evaluating wide-field-of-view augmented reality with mixed reality simulation. In 2016 IEEE Virtual Reality (VR), pp 93–102. IEEE

Riccio GE, Stoffregen TA (1991) An ecological theory of motion sickness and postural instability. Ecol Psychol 3(3):195–240

Rietzler M, Deubzer M, Dreja T, Rukzio E (2020) Telewalk: towards free and endless walking in room-scale virtual reality. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, pp 1–9

Risi D, Palmisano S (2019) Effects of postural stability, active control, exposure duration and repeated exposures on hmd induced cybersickness. Displays 60:9–17

Ryge AN, Vollmers C, Hvass JS, Andersen LK, Berthelsen T, Bruun-Pedersen JR, Nilsson NC, Nordahl R (2018) A preliminary investigation of the effects of discrete virtual rotation on cybersickness. In 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 675–676. IEEE

Sagnier C, Loup-Escande E, Valléry G (2019) Effects of gender and prior experience in immersive user experience with virtual reality. In: International conference on applied human factors and ergonomics, pp 305–314. Springer

Sakai H, Harada T, Larroque SK, Demertzi A, Sugawara T, Ito T, Wada Y, Fukunaga M, Sadato N, Laureys S (2021) Left parietal involvement in motion sickness susceptibility revealed by multimodal magnetic resonance imaging. Hum Brain Mapp. https://doi.org/10.1002/hbm.25710

Sakhare AR, Yang V, Stradford J, Tsang I, Ravichandran R, Pa J (2019) Cycling and spatial navigation in an enriched, immersive 3d virtual park environment: a feasibility study in younger and older adults. Front Aging Neurosci 11:218

Saredakis D, Szpak A, Birckhead B, Keage HAD, Rizzo A, Loetscher T (2020) Factors associated with virtual reality sickness in head-mounted displays: a systematic review and meta-analysis. Front Hum Neurosci 14:96. https://doi.org/10.3389/fnhum.2020.00096

Sarupuri B, Hoermann S, Steinicke F, Lindeman RW (2017) Trigger-walking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In: Proceedings of the 5th symposium on spatial user interaction, pp 138–147. https://doi.org/10.1145/3131277.3132177

Schöberl F, Zwergal A, Brandt T (2020) Testing navigation in real space: contributions to understanding the physiology and pathology of human navigation control. Front Neural Circ 14:6. https://doi.org/10.3389/fncir.2020.00006

Sevinc V, Berkman MI (2020) Psychometric evaluation of simulator sickness questionnaire and its variants as a measure of cybersickness in consumer virtual environments. Appl Ergon 82:102958

Shafer DM, Carbonara CP, Korpi MF (2017) Modern virtual reality technology: cybersickness, sense of presence, and gender. Media Psychol Rev, 11(2)

Shafer DM, Carbonara CP, Korpi MF (2019) Factors affecting enjoyment of virtual reality games: a comparison involving consumer-grade virtual reality technology. Games Health J 8(1):15–23

Shahid Anwar M, Wang J, Ahmad S, Ullah A, Khan W, Fei Z (2020) Evaluating the factors affecting qoe of 360-degree videos and cybersickness levels predictions in virtual reality. Electronics 9(9):1530. https://doi.org/10.3390/electronics9091530

Shi R, Liang HN, Wu Y, Yu D, Xu W (2021) Virtual reality sickness mitigation methods. Proc ACM Comput Graph Interact Techn 4:1–16

Smith SP (2021) Comparing virtual environments for cybersickness using a cumulative optical flow entropy metric. IEEE Access 9:68898–68904

So RH, Yuen S (2007) Comparing symptoms of visually induced motion sickness among viewers of four similar virtual environments with different color. In: International Conference on Virtual Reality, pp 386–391. Springer

So RH, Lo W, Ho AT (2001) Effects of navigation speed on motion sickness caused by an immersive virtual environment. Hum Factors 43(3):452–461

Somrak A, Humar I, Hossain MS, Alhamid MF, Hossain MA, Guna J (2019) Estimating vr sickness and user experience using different hmd technologies: an evaluation study. Future Gener Comput Syst 94:302–316

Sra M, Jain A, Maes P (2019) Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–14

Stanney KM, Kennedy RS, Drexler JM (1997) Cybersickness is not simulator sickness. In: Proceedings of the Human Factors and Ergonomics Society annual meeting, volume 41, pp 1138–1142. SAGE Publications Sage CA: Los Angeles, CA

Stanney K, Fidopiastis C, Foster L (2020) Virtual reality is sexist: but it does not have to be. Frontiers in Robotics and AI, 7(4)

Stanney K, Lawson BD, Rokers B, Dennison M, Fidopiastis C, Stoffregen T, Weech S, Fulvio JM (2020) Identifying causes of and solutions for cybersickness in immersive technology: reformulation of a research and development agenda. Taylor and Francis, 36:1783–1803, 11

Stauffert JP, Niebling F, Latoschik ME (2018) Effects of latency jitter on simulator sickness in a search task. In: 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 121–127. IEEE

Stauffert JP, Niebling F, Latoschik ME (2020) Latency and cybersickness: impact, causes and measures. a review. Front Virtual Real 1:31

Stone WB III (2017) Psychometric evaluation of the Simulator Sickness Questionnaire as a measure of cybersickness. PhD thesis, Iowa State University

Szpak A, Michalski SC, Saredakis D, Chen CS, Loetscher T (2019) Beyond feeling sick: the visual and cognitive aftereffects of virtual reality. IEEE Access 7:130883–130892

Teixeira J, Palmisano S (2020) Effects of dynamic field-of-view restriction on cybersickness and presence in hmd-based

virtual reality. Virtual Real 25:433–445. https://doi.org/10.1007/s10055-020-00466-2

Terenzi L, Zaal P (2020) Rotational and translational velocity and acceleration thresholds for the onset of cybersickness in virtual reality. In: AIAA Scitech 2020 Forum, p 0171. https://doi.org/10.2514/6.2020-0171

Tian N, Clement R, Lopes P, Boulic R (2020) On the effect of the vertical axis alignment on cybersickness and game experience in a lying-down posture. In 2019 IEEE conference on games (CoG), pp 1–8. IEEE

Tian N, Clément R, Lopes P, Boulic R (2020) On the effect of the vertical axis alignment on cybersickness and game experience in a supine posture. In 2020 IEEE Conference on Games (CoG), pp 359–366. IEEE

Tiiro A (2018) Effect of visual realism on cybersickness in virtual reality. University of Oulu, 350

Treisman M (1977) Motion sickness: an evolutionary hypothesis. Science 197(4302):493–495

Tychsen L, Foeller P (2020) Effects of immersive virtual reality headset viewing on young children: visuomotor function, postural stability, and motion sickness. Am J Ophthalmol 209:151–159

Vailland G, Gaffary Y, Devigne L, Gouranton V, Arnaldi B, Babel M (2020) Vestibular feedback on a virtual reality wheelchair driving simulator: a pilot study. In: Proceedings of the 2020 ACM/IEEE International conference on human-robot interaction, pp 171–179

Vasylevska K, Yoo H, Akhavan T, Kaufmann H (2019) Towards eye-friendly vr: how bright should it be? pp 566–574. https://doi.org/10.1109/VR.2019.8797752

Venkatakrishnan R, Venkatakrishnan R, Anaraky RG, Volonte M, Knijnenburg B, Babu SV (2020) A structural equation modeling approach to understand the relationship between control, cybersickness and presence in virtual reality. In: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 682–691. IEEE

Venkatakrishnan R, Venkatakrishnan R, Bhargava A, Lucaites K, Solini H, Volonte M, Robb A, Babu SV, Lin WC, Lin YX (2020) Comparative evaluation of the effects of motion control on cybersickness in immersive virtual environments. In: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 672–681. IEEE

Wang Y, Zhai G, Chen S, Min X, Gao Z, Song X (2019) Assessment of eye fatigue caused by head-mounted displays using eye-tracking. Biomed Eng Online 18(1):1–19

Wang Y, Chardonnet JR, Merienne F (2019) Vr sickness prediction for navigation in immersive virtual environments using a deep long short term memory model. In: 2019 IEEE conference on virtual reality and 3D user interfaces (VR), pp 1874–1881. IEEE

Wang Y, Chardonnet JR, Merienne F, Ovtcharova J (2021) Using fuzzy logic to involve individual differences for predicting cybersickness during vr navigation. In 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pp 373–381. IEEE

Wang B, Rau PLP (2019) Effect of vibrotactile feedback on simulator sickness, performance, and user satisfaction with virtual reality glasses. In: International conference on human-computer interaction, pp 291–302. Springer

Weech S, Varghese JP, Barnett-Cowan M (2018) Estimating the sensorimotor components of cybersickness. J Neurophysiol 120(5):2201–2217

Weech S, Kenny S, Barnett-Cowan M (2019) Presence and cybersickness in virtual reality are negatively related: a review. Front Psychol 10:158

Weech S, Kenny S, Lenizky M, Barnett-Cowan M (2020) Narrative and gaming experience interact to affect presence and cybersickness in virtual reality. Int J Hum Comput Stud 138:102398

Weech S, Wall T, Barnett-Cowan M (2020) Reduction of cybersickness during and immediately following noisy galvanic vestibular stimulation. Exp Brain Res 238(2):427–437

Weißker T, Kunert A, Fröhlich B, Kulik A (2018) Spatial updating and simulator sickness during steering and jumping in immersive virtual environments. In: 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp 97–104. IEEE

Wibawa AD, Mardi S, Nugroho S, Khoirunnisaa AZ et al (2019) Eeg visualization for cybersickness detection during playing 3d video games. In: 2019 International seminar on intelligent technology and its applications (ISITIA), pp 325–330. IEEE

Wibirama S, Nugroho HA, Hamamoto K (2018) Depth gaze and ecg based frequency dynamics during motion sickness in stereoscopic 3d movie. Entertain Comput 26:117–127

Widyanti A, Hafizhah HN (2021) The influence of personality, sound, and content difficulty on virtual reality sickness. Virtual Real 1–7. https://doi.org/10.1007/s10055-021-00525-2

Wienrich C, Weidner CK, Schatto C, Obremski D, Israel JH (2018) A virtual nose as a rest-frame-the impact on simulator sickness and game experience. In: 2018 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games), pp 1–8. IEEE

Williams NL, Peck TC (2019) Estimation of rotation gain thresholds considering fov, gender, and distractors. IEEE Trans Vis Comput Graph 25(11):3158–3168

Yamamura H, Baldauf H, Kunze K (2021) Hemodynamicvr-adapting the user's field of view during virtual reality locomotion tasks to reduce cybersickness using wearable functional near-infrared spectroscopy. In: ACM international conference proceeding series, pp 223–227

Yildirim C (2020) A review of deep learning approaches to eeg-based classification of cybersickness in virtual reality. In: Proceedings—2020 IEEE International conference on artificial intelligence and virtual reality, AIVR 2020, pp 351–357

Yildirim C (2019) Cybersickness during vr gaming undermines game enjoyment: a mediation model. Displays 59:35–43

Young SD, Adelstein BD, Ellis SR (2007) Demand characteristics in assessing motion sickness in a virtual environment: or does taking a motion sickness questionnaire make you sick? IEEE Trans Vis Comput Graph 13(3):422–428

Zhong W, Shahbaz O, Teskey G, Beever A, Kachour N, Venketaraman V, Darmani NA (2021) Mechanisms of nausea and vomiting: current knowledge and recent advances in intracellular emetic signaling systems. Int J Mol Sci 22(11):5797

Zielasko D (2021) Subject 001—A detailed self-report of virtual reality induced sickness. In: Proceedings—2021 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops, VRW 2021, pp 165–168. https://doi.org/10.1109/VRW52623.2021.00038

Żukowska M, Buń P, Górski F, Starzyńska B (2019) Cyber sickness in industrial virtual reality training. In: International scientific-technical conference manufacturing, pp 137–149. Springer