A Literature Review of Factors Influencing Cybersickness in 360° Video Experiences

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Abstract

Omnidirectional videos, or 360°-videos represent an entry point to immersive media. However, watching 360°-videos in head-mounted displays may evoke symptoms related to cybersickness. This literature review investigates the underexplored area of cybersickness induced by 360° videos when viewed through head-mounted displays. While cybersickness has been studied extensively in interactive virtual reality (6 DOF), its manifestations and triggers in the area of 360°-videos (3 DOF) remain less understood. By evaluating 52 selected articles, we discerned and categorized key factors influencing cybersickness into four groups: Technical, human-related, context and content, and experience-related factors. Overall, our review highlights that the specific characteristics of 360°-video, such as recording and streaming technologies, limited agency, and having only 3-DOF, have been neglected in cybersickness research so far. By that, this review emphasizes the need for more systematic (long-term) studies about influencing factors. We also highlight the need for models predicting and estimating cybersickness and longitudinal studies to enhance the 360°-video experience and ensure its broader acceptance beyond academia.

Keywords: 360° Video, cybersickness, comfort, head-mounted display, influencing factors, simulator sickness, virtual reality

1 Introduction

Cybersickness is an umbrella term for various symptoms such as nausea, eye strain, or headaches [12], commonly associated with immersive media such as virtual reality and 360°-video. These symptoms may occur during and after exposure to a Virtual Environment (VE) [16]. Several studies have already investigated and reviewed cybersickness — sometimes referred to as simulator sickness — and covered a variety of factors [5,9,16,40,41,43,61,62,68]. We provide a more detailed overview of those studies in Sect. 2[1].

360°-videos (also referred to as omnidirectional) often represent an entry point to immersive media and may be delivered using "classical" video streaming approaches [18]. While watching such videos, the user typically sits (or sometimes stands or lies) and rotates their head and/or body to explore the video content. The 3-DOF (degrees of freedom) nature distinguishes this media type from actual VR applications that allow a 6-DOF interaction. It removes the impact of locomotion as a source of cybersickness but also introduces a mismatch between the user's head motion and their visual perception because translations of the head are not reflected in translations of the virtual camera, and possible camera motion does not match head or body motion. In addition to that, users have less (or no) agency in the scene as they are only observers, experiencing either video recordings of real places or, in some cases, computer-generated 360° videos delivered via efficient video streaming (more about these factors in Sect. 2.1). These aspects — limited locomotion, limited agency, reliance on recordings of real places or computer-generated 360° videos, and video streaming — do not only highlight the difference to 6-DOF VR. They also highlight unique characteristics of 360°-videos that may influence cybersickness. For example, aspects related to video quality, such as encoding, stitching quality, and streaming approaches, are now additional relevant factors that need to be considered (next to general factors such as latency).

As with any immersive media, various authors have shown that 360°-videos evoke cybersickness symptoms [17,31,38,42,72,73]. A study by Saredakis et al. [68] even suggests that 360°-videos evoke the second highest simulator sickness scores, only outranked by gaming content (next to minimalistic content and scenic content). Similarly, recent studies have found that many participants experienced at least some cybersickness when viewing 360°-videos [31,42].

We contribute the following key aspects:

1. We present a review of articles investigating cybersickness in 360°-videos, categorize the influencing factors (technical, human-related, contextual and content, and experience-related factors), discuss the categories, and contrast the findings from 6-DOF virtual reality. This result is a reference point for future research on cybersickness in 360°-videos.
2. We advance the fundamental understanding of cybersickness by investigating into 360°-videos and contrasting the similarities and differences between the factors influencing cybersickness in traditional VR and 360°-videos.
3. We define key research challenges centred around 360°-videos that must be addressed (among others, streaming technologies, ergonomics, posture, video duration) and on more general open problems (temporal modelling, longitudinal studies, mitigation techniques) to guide future research.

With these three contributions, our paper informs and guides research by outlining the current state of the art regarding factors influencing cybersickness in 360°-video and identifies critical challenges. It contributes to the advancement of immersive media by providing guidance and pointers on reducing and mitigating cybersickness in 360°-videos.

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[1]Throughout this paper, we use the term cybersickness unless the work explicitly uses a moving-base simulator, such as a flight simulator, following the definitions in Doerner et al. [15, Sec 2.4.7]. We do this even if the cited authors use the Simulator Sickness Questionnaire (SSQ) to measure cybersickness and, by that, maybe measure the false construct [81].

2 Related Work

2.1 The difference between 6-DOF VR and 360°-videos

Previous papers have discussed a variety of different aspects related to cybersickness. However, most existing papers do not distinguish between 6-DOF VR and 360°-video or focus only on 6-DOF VR. We believe it is crucial to focus on 360°-video separately because it varies significantly from 6-DOF VR, especially regarding viewport control. In both 360°-videos and 6-DOF VR, content is viewed via a head-mounted display. Contrary to 6-DOF VR, 360°-videos typically only allow for rotational movements (yaw, pitch, roll) and not translatory movements of the virtual camera. This removes the impact of locomotion techniques, which have been shown to impact cybersickness symptoms [91]. In addition, in 360°-videos, users cannot interact with the environment, removing the crucial aspect of "agency" which positively contributes to the sense of presence [34] in virtual environments, and presence has been shown to influence cybersickness (c.f. Sect. 3.5.2). Also, the level of agency has been shown to influence the severity of cybersickness symptoms [80] and thus, adds to the difference between 6-DOF VR and 360°-videos. Next to these more human-computer-interaction-focused implications, the content for 360°-videos is often not computer-generated but in the form of video footage, which poses technical challenges regarding streaming and encoding. Here, real-time transmission of large amounts of video data, as well as real-time resolution switching and encoding to save bandwidth, pose challenges. If either (or both) does not work sufficiently well, perceived quality suffers, and cybersickness symptoms can potentially occur or be increased (cf., e.g., [72]). Because of these differences, we have decided to perform a dedicated review, investigating what contributes to cybersickness in 360°-videos, what the differences to VR are, and if factors specific to 360°-videos (such as bitrate or streaming technology) have been appropriately investigated.

2.2 Cybersickness research

Research on cybersickness has a long history, and many studies investigated individual factors. For example, an extensive collection of papers investigates technological factors [41,43,61,68]. However, they do not distinguish between 360°-videos and 6-DOF VR or investigate only 6-DOF VR. Similarly, researchers focused on human factors [14,16,46] and constructs such as presence [89]. Summarizing many of these studies, Stanney et al. [79] presented a research agenda to address challenges related to cybersickness in Extended reality (XR) environments. Based on their findings, they recommend, for example, prioritizing the creation of lightweight, powerful HMDs, reducing latencies, and understanding the implications of cybersickness on user performance. These recommendations are relatively general as they focus on immersive media, including augmented reality, virtual reality, and 360°-video. By that, however, media-specific factors are less prominent in their agenda.

Several other review papers investigate cybersickness and provide classification systems for factors related to cybersickness (and inspire our work). However, no previous review paper focuses on 360°-video and provides a holistic overview of factors or even categories of factors. For example, Bockelman et al. [5] summarized and grouped cybersickness factors for 6-DOF VR into the categories "system", "task", and "individual differences". Rebentisch et al. [62] categorized the factors into "demographics", "hardware" and "software". Chandra et al. [59] classified the factors into four categories: "human", "display type", "VR content", and "design (virtual environment)". In Davis et al.'s review [12], the authors categorized factors that affect VR experiences into "individual factors", "device factors", and "task factors". The same applies to the review of Chang et al. [9], who classify the factors into "hardware", "content", and "human-related factors". Tian et al. [85] present a comprehensive review focusing on cybersickness theories, measures, mitigation techniques, prediction, and factors (content, interaction, human, hardware, experimental). In addition, research on measuring cybersickness is gaining traction (e.g., Yang et al. [92] provide a systematic review of machine-learning-based measuring techniques). Other survey and review papers focus on cybersickness reduction (e.g., Ang et al. [1], who report on various approaches covering content, hardware, design, and non-technical reduction techniques), implicitly covering underlying factors.

When summarizing these existing review papers on cybersickness in the domain of immersive media, a critical insight relevant to our work stands out: All reviews focus on 6-DOF VR and, by that, overlook the difference between VR and 360°-video (cf. Sect. 2.1). However, factors relevant to the latter, such as bitrate, streaming methods, or the absence of 6-DOF locomotion do influence cybersickness and, thus, need to be part of a thorough overview of cybersickness in 360°-video. Consequently, while we provide "another" review about cybersickness, we specifically focus on 360°-videos, highlighting differences, similarities, and unique aspects. Further, we provide a comprehensive review of the factors influencing cybersickness in HMD-based 360°-video. While many relevant factors will align between 360°-videos and 6-DOF VR, this review aims to identify and summarize factors specific to 360°-videos.

3 Review of Influencing Factors

3.1 Review methodology

On the 30. July 2024, we performed a literature search on the database Web Of Science [2] using the following search terms:

(*"omnidirectional video"* OR *"360"*) AND (*"sickness"* OR *"cybersickness"* OR *"simulator sickness"*)

This search resulted in 199 articles. We did not apply additional research-quality criteria as Web of Science is well curated. We assigned the initial analysis of 199 papers evenly among 4 authors (e.g., papers 1-50 to author 1, 51-100 to author 2, etc.) and skimmed the papers. Articles that (1) did not investigate factors influencing cybersickness or (2) reported on factors influencing cybersickness outside the domain of 360°-videos were excluded. Next, we checked the full text of these papers concerning the aforementioned two criteria. This reduced the corpus size to 27 papers (13.6% of 199). In addition, we added a corpus of literature based on the authors' expertise (12 papers, i.e., own publications and known key papers). Out of the $12+27=39$ papers, we checked references for additional relevant literature, applying the same criteria as above. This resulted in another 13 articles. The final corpus comprises 52 papers. None of the papers discussed in Sect. 2 are in the final corpus as none focused on 360°-video.

In the following sections, we identify and categorize factors from these articles that influence cybersickness. We group these factors into four subcategories, created inductively after having read all 52 papers: (i) technical factors, (ii) human factors, (iii) context & content, and (iv) experience-related factors. These categories were refined through several discussion rounds among the first four authors and mostly align with previous category systems (c.f., Sect. 2.2). For example, "system" and "individual differences" from Bockelmann et al. [5] are similar to our categories "technical factors" and "human factors". We grouped previous factors such as "VR content" and "design (virtual environment)" [61] into one group "context & content". No prior work included a category that specifically grouped "experience-related factors". Note: similar to prior articles outlined in Sect. 2, we removed factors that are not relevant nowadays, such as phosphorus lag.

[2] https://www.webofscience.com/wos/woscc/summary/67471d5d-f366-4747-9e99-3e569ba1af36-86c1c883/relevance/1

3.2 Technical factors

The technical setup has an enormous effect on the severity of cybersickness. In general, the consensus seems to be that an HMD with better technical specifications (higher resolution and faster refresh rate) leads to less cybersickness compared to an HMD with lower technical specifications [23, 67]. However, a 2D screen such as a TV often leads to even lower cybersickness [10, 23, 28]. Nevertheless, Taylor et al. [84] show this is not always the case. In their study, participants of three non-immersive conditions did not report fewer or lower cybersickness symptoms compared to the condition of watching a 360°-video. Additionally, the differences in cybersickness symptoms between various conditions, including watching a 360°-video, were not statistically significant. They point out that their videos' photorealism, the devices' high refresh rate, or the different field-of-views in the conditions could be the reason for their results. Their study provides no analysis or follow-up studies to explain these findings. They suggest that further research is needed to explore which technical factors contribute to the severity of symptoms or to understand potential interdependencies between factors when watching 360°-videos.

To this aim, in this section, we briefly summarize the individual research on cybersickness related to 360°-videos, grouped by factors related to the display (e.g., resolution or lag) and the video data (e.g., resolution or frame rate).

3.2.1 Display / hardware

The physical display is the primary interface between humans and a virtual environment, and it has an enormous impact on cybersickness symptoms in 360°-videos.

One investigated factor related to cybersickness in 360°-video is **motion-to-high-resolution latency** in adaptive streaming solutions. Motion-to-*high-resolution* latency refers to "the time it takes between a user moving their head to a new viewport and high-resolution imagery becoming available in the viewport". Singla et al. investigated the effect of motion-to-high-resolution latency on cybersickness ratings and perceived video quality [73]. They found that network delay does not influence the scores of cybersickness, as a low-resolution video was always available (and sooner than the high-resolution image, in case that was provided). Thus, actual motion-to-photon latency was always low in their experiment [73]. Future investigations on motion-to-photon latency would complement this research.

It is generally hard to compare or investigate the individual influence of particular device specifications, as commercially available devices often differ in multiple dimensions and ergonomics. Thus, the **device type** is an overall relevant factor encompassing several technical specifications. For example, Guna et al. [28, 29] compared SSQ scores for different HMDs (among others, Oculus Rift DK 1 (640×800 per eye), Oculus Rift DK 2 (960×1080 per eye), Oculus Rift CV 1 (1080×1200 per eye)). Experimental results showed that users feel less prone to cybersickness with increasing **display resolution**. However, when comparing the technical specifications of all three versions of Oculus Rift, these are different in terms of display resolution, refresh rate, and FOV. Consequently, it is unclear if the reduction in SSQ scores is due to the display resolution, refresh rate, FOV, or a combination of all these factors. Similarly, Singla et al. [72] also compared cybersickness ratings for HTC Vive and Oculus Rift CV1. Here, both have similar technical specifications in terms of resolution (2160×1200), refresh rate (90 Hz), and FOV (110°). Results were inconclusive as some users have experienced more sickness in HTC Vive than Oculus Rift CV1 and vice versa. Other factors, such as different rendering algorithms and comfort ratings, could be a reason for this. Finally, Singla et al. [72, 74] conducted subjective tests with HTC Vive (Resolution 2160×1200) and HTC Vive Pro (Resolution 2880×1600) with the same 360°-videos. The display type, refresh rate (90Hz), and FOV (110°) for HTC Vive and HTC Vive Pro are the same — they only differ in display resolution. From their tests, it can be concluded that the display resolution impacts the scores of cybersickness, with higher resolution leading to lower scores — interestingly, irrespective of video resolution.

Mur-Spiegl et al. [52] compared cybersickness and presence in low-quality and high-quality HMDs. Their results showed that a higher quality HMD has a positive effect on the experienced presence, but the impact of HMDs on cybersickness scores was insignificant. In this paper, there was no investigation into the relationship between presence and cybersickness.

3.2.2 Video / signal

Many factors associated with videos (or the video signal), such as resolution, motion, and frame rate, can contribute to cybersickness when watching 360°-video. Regarding **video resolution**, Singla et al. [72] investigated the impact of this factor on the scores of cybersickness. They found that users feel less prone to cybersickness with a video resolution of 4K than Full High Definition (FHD) when the display resolution is the same (meaning that both higher video resolution and higher display resolution lead to less severe cybersickness symptoms).

Raake et al. [58] investigated the impact of **bitrate** on cybersickness (or, here, comfort, i.e., an inverse-sickness acquired via a single-scale question). Their results indicate that users felt less cybersickness at higher bit rates than lower bit rates when they did not change the resolution. It may be noted, however, that test participants may have used the single scale with a bias toward judging visual quality rather than actual cybersickness-related comfort.

To reduce symptoms, a real-time optical flow estimation method based on the user's viewport was proposed in [8]. By incorporating Granulated Rest Frames (GRFs)—stable, noise-like visual elements—this method reduces sensory conflict, minimizing oculomotor strain and disorientation. While a pilot study showed potential in reducing discomfort, results were not statistically significant due to a small sample size, indicating a need for further research.

3.2.3 Optical Flow and Disparity in 360°-videos

Optical flow and disparity are essential elements in the QoE of 360°-videos, and can, if improperly managed, lead to discomfort.

Optical flow refers to the perceived motion of visual elements as a user moves within a scene [32, 90]. In 360°-videos, a user can view in any direction, leading to complex optical flow patterns and effects due to a possibly moving camera. Improper handling of these patterns can lead to a mismatch between perceived and actual motion, contributing to discomfort or cybersickness.

Disparity refers to the difference in images between the left and right eyes. Due to this disparity, the brain perceives depth. If the disparity information is not accurate, it may cause visual discomfort. [32, 54].

Specifically, focusing on video characteristics such as optical flow and disparity was beyond the initial scope of our objectives.

3.2.4 Discussion

Considering the technical factors, only a few (namely motion-to-high-resolution latency, display resolution, device type, video resolution, and bitrate) have been investigated in 360°-videos and cybersickness. Overall, where aligned between technologies, these results agree with previous research on VR in that these factors influence cybersickness and that better technical specifications lead to less severe symptoms. Still, a better understanding is necessary as some results are conflicting or inconclusive. For example, when comparing Oculus Rift DK1 to Oculus Rift DK2 in VR, Shafer et al. [69] did not find significant differences in cybersickness symptoms' severity. This does not agree with the results of Singla et al. in 360°-video [72, 74]. A more structured and fine-grained analysis of the individual technology-related factors' influence is necessary to foster a better understanding of cybersickness in 360°-video. A core challenge here is a hardware setup (e.g., a modular HMD) that allows for isolating these factors for experiments. It is important to note that many other relevant factors have not been thoroughly researched yet — specifically for 360°-videos — such as the influence of framerate, different lenses, different algorithms for rendering (e.g., monoscopic and bi-ocular [61]), or streaming types [93]. This also includes factors such as the impact of vari- and multi-focal displays, depth-of-field, and 3-DOF tracking errors. In addition to that, Zink et al. [95] suggest that network features, such as delay, fluctuations in data transmission, the capacity of the network, the ratio of the quality of the view or tile, and aspects of streaming like interruptions may be considered as relevant when it comes to cybersickness.

Finally, apart from the technical parameters of the display, it has been shown that HMD weight and pressure load on the nose affect users' discomfort scores. For example, Souchet et al. [77] found a negative relationship between HMD weight and discomfort scores in 6-DOF VR. However, the impact in the 3-DOF case with different movement characteristics (e.g., the absence of translatory movements) for 360°-video has not been adequately researched yet. Thus, the impact of ergonomic factors such as weight distribution or heat dissipation needs to be investigated to better understand the impact on cybersickness when watching 360°-videos (e.g., for 90 minutes 360°-movies). This should then result in proper ergonomic guidelines.

In summary, many factors, such as display resolution, refresh rate, and device type, influence 360° videos and VR experiences. However, many general factors like motion-to-high-resolution latency, adaptive tile-based streaming, and specific projection schemes are more unique to 360°-videos. Further research would be necessary to identify and systematically analyze these factors' relevance to cybersickness.

3.3 Human factors

Humans' individual characteristics may play a determining role in susceptibility to cybersickness. In the following paragraphs, we elaborate on findings related to physical/physiological and behavioural factors to put them in perspective with findings from VR.

3.3.1 Age

In our corpus, one study [24] investigated the effect of age by comparing cybersickness symptoms with 360°-hazardous-driving-videos among three different age groups but found no significant differences. We consider that further research on the effect of age on cybersickness is necessary to better understand possible interrelations.

3.3.2 Gender

We note that in the studies evaluated in the following, none of the authors specified how/if they explicitly inquired about gender — many simply reported results using the term "gender". Therefore, it is unclear whether these studies referred to biological sex or self-identified gender.

Melo et al. [48] evaluated differences in passive scenarios[3] with 1–7 minute long videos and found no differences between men and women for their reported cybersickness. However, Narciso et al. [53] evaluated 360°-videos in 2D vs 3D, and their results found that women reported higher nausea in the 2D video condition compared to men, who reported higher nausea in the 3D video condition. Jun et al. [35] performed a large study with 511 participants evaluating 360°-videos. In their study, all participants reported relatively low SSQ scores, and their statistical analysis found that women were giving higher cybersickness scores than men. Similarly, other studies [20, 70, 72] found that women reported higher SSQ scores than men when watching 360°-videos. Also, Groth [27] found differences between men and women when using Galvanic Vestibular Stimulation (GVS) to reduce cybersickness. The authors mentioned that although it showed significant reductions for both women and men, men tended to spend more time watching 360°-videos with GVS than women.

[3]Passive viewing refers to the experience in which participants are stationary and move their heads to explore the videos.

3.3.3 Posture

The Postural Instability theory proposes that cybersickness occurs when the mechanisms for maintaining postural stability are compromised [65]. However, Dennison & D'Zmura [13] found only a weak relation between postural instability and cybersickness ratings. Litleskare [45] examined postural stability deterioration while watching 360°-videos in healthy active adults, with findings suggesting that postural stability can be a predictor and an objective measure of cybersickness.

Rothe et al. [66] investigated the effect of various body postures on cybersickness when watching 360°-videos. The authors showed videos recorded in a posture opposite to the participants' current posture. For example, the participants watched videos captured from a sitting position while standing and vice versa. Their findings showed no differences in the severity of cybersickness caused by posture mismatches. However, participants desired to change to a sitting posture for both recording angles.

3.3.4 Previous experiences with HMDs and a familiarization period

Prior and repeated experience with 360°-videos may reduce cybersickness symptoms, but results are inconclusive. Anwar et al. [70] found that participants who watched 360°-videos weekly reported lower SSQ scores than first-time participants or participants who rarely watched 360°-videos. However, Elwardy et al. [17] found contradictory results where SSQ scores are similar irrespective of their experience level during their first exposure to an unfamiliar stimulus in 360°-videos. For instance, one of their key results was that participants with limited or no experience with HMDs reported higher SSQ scores in subsequent exposure to the same stimulus. Sumayli et al. [82] investigated the impact of familiarization on SSQ scores through repeated exposure to 360°-videos. Contrary to the other studies, their results did not find significant differences when comparing the first and second exposures. The findings of the aforementioned studies may hint at the need for controlling confounding factors in studies to determine the effect of previous experiences and repeated exposure to 360°-videos.

3.3.5 Discussion

Different authors have mentioned age as an influencing factor of motion sickness [3, 39, 49, 57, 68] in VR. However, these findings differ from 360°-videos, where a study found no significant differences among age groups [24]. To the best of our knowledge, there have not been other studies that investigate the influence of age in 360°-videos. Further investigations with different age groups, especially with participants over 45 years, can help to identify differences in the level of cybersickness experienced, if any, when aging. Additionally, posture may act as a mediating factor and should be examined in future studies to better understand its influence on cybersickness.

The influence of gender presents similarly contradicting findings in 360°-videos and VR. While it has been suggested that women tend to be more susceptible to cybersickness than males [60], we outlined the contradicting results for 360°-videos. Biocca [4] suggested that previous results from 6-DOF VR were partially based on self-reports and that men may underestimate their susceptibility to motion sickness. In general, the consideration of gender is a prevalent issue in human-computer interaction and should be treated more carefully by researchers [25, 47, 78].

Regarding behavioral factors, the posture stability theory has been mentioned as a factor that induces cybersickness in both VR and 360°-videos. In VR, different studies [43, 60, 88] show or contrast [94] the advantages of sitting over standing. Additionally, some authors [2, 51] mentioned that it could be used as a predictor of cybersickness. Findings in both VR and 360°-videos suggest sitting as a measure to avoid cybersickness symptoms, especially when the purpose of the study is not solely the investigation of cybersickness.

Previous experiences with HMDs or gaming experience have been mentioned to influence cybersickness in VR, and some findings differ — again — from those of 360°-videos. For instance, Kennedy et al. [37] and Regan et al. [63] found that repeated interactions with a VR will decrease symptoms of motion sickness among users. Freitag et al. [19] also showed that participants who do not have prior experience have higher discomfort scores. However, previous studies [21, 22] did not find a relationship between gaming experience and cybersickness. Also, other psychological factors have been found to influence cybersickness in VR, such as pain catastrophizing [50], which may also influence watching 360°-videos. In general, we consider that there is still room to investigate if gaming or previous experiences and psychological factors affect cybersickness, primarily as no study investigated the effect of cybersickness for 360°-videos over an extended period (several weeks, months, or years).

To summarize, some human-related influencing factors show variations in 360°-videos compared to those in VR. We call for caution regarding all human-related influencing factors, as most have been analyzed separately, leaving aside possible interaction effects. Further, human-related factors may be influenced by contextual or technical factors.

3.4 Context & content factors

Cybersickness may also be influenced by test-specific factors such as various types of video content and the amount of time spent watching an 360°-video.

3.4.1 Video Content

We can divide video content-related aspects into (i) the speed of motion in the content, (ii) the effects of 3D content in 360°videos, and (iii) the camera motion and position when recording videos.

Speed of camera motion and the movement of objects in the content. Fast motions and excessive movements in content influence the severity of cybersickness-related symptoms during or after watching videos. Guna et al. [28, 29] investigated the impact of different video contents in combination with 3 different HMDs and a 2D TV screen. The authors evaluated the effect of two types of content, i.e., *"neutral content"* (slow) and *"action content"* (fast). The reported cybersickness severity of the *"action content"* was higher than that of the *"neutral content"* for all HMDs. Similarly, in the study of Singla et al., [72], content with fast motion led to higher cybersickness scores than videos with slower motion. Also, Anwar et al. [70] compared videos with fast, medium, and slow motion and found a positive correlation between the speed of the content and cybersickness scores, i.e., the higher the speed, the higher the reported cybersickness scores. Tran et al. in [86] showed that low- or medium-motion content evoked higher comfort ratings than fast-motion content. Here, higher ratings show that the participants felt more comfortable. In a subsequent study, Tran et al. [83] added 3 more videos to their evaluation, which showed similar results. Also, Groth et al. [27] investigated the impact of content characteristics on cybersickness using a video with little movement and slow motion (video of a walk) and a video with a lot of movement and fast motion (video of a mountain bike ride). Here, the authors tracked the discomfort values by asking the participants to press a button when their discomfort increased or use the controller's touchpad when their well-being increased. As soon as the fast-motion video started playing, the discomfort scores increased instantly. These discomfort scores continued to rise throughout the experiment, given that the fast-motion content was being played. Hence, it can be concluded that the severity of cybersickness is influenced by the presence of fast or excessive motions in videos, which can affect the overall user experience.

Different effects of 3D content in 360°videos. Narciso et al. [53] investigated the influence of video format (monoscopic vs. stereoscopic) on cybersickness. They did not find any effect of the video format on cybersickness (overall SSQ scores between 8.46 and 12.47) or presence. They also investigated audio (2D, 3D), revealing no significant differences. This suggests that having stereoscopic content does not increase cybersickness. Another factor of the video's content, according to Choy et al. [10], is the nature of movement in the 3D video: Content that is relatively still and shows less chaotic motion (such as a garden scene with natural elements like a lake, trees, and birds) led to less severe symptoms than a wishing well's noisy water surface.

Camera motion and position when recording videos. Camera motions and the recording position can affect cybersickness. In the study of Anwar et al. [70], three different camera motion types were compared: fixed camera (no motion), vertical motion, and horizontal motion. Here, the fixed camera led to the lowest cybersickness scores and the vertical motions led to the highest scores across conditions. They also compared the number of moving targets in videos, where having multiple targets led to the highest cybersickness scores. Also, Rothe et al. [66] showed that a mismatch between the camera position while recording a video and the actual eye height can lead to increased cybersickness. If the video was recorded from a higher perspective than the viewer's position, it increases cybersickness. However, when the camera position matches or is lower than the subject's point of view, cybersickness values remain stable. In summary, camera motions and recording positions significantly impact cybersickness experiences.

3.4.2 Duration of Task

Sumayli et al. [82] conducted a test with 30 minutes of watching an 360°-video in an HMD. After each minute, the sickness ratings were captured using a 7-point Likert scale. Reported scores started to increase after the eighth minute. These findings align with those of Melo et al. [48]. The authors investigated four different exposure times (1, 3, 5, and 7 min), showing no significant differences in cybersickness scores. Similarly, Singla et al. [71, 75] showed that SSQ scores tend to increase as the test progresses, indicating that the later sessions are given higher scores than the earlier sessions. Additionally, a study noted that extended use of VR headsets caused eye strain and fatigue in participants [87]. However, it may not always be the case, as some users may adapt to the viewing environment, reducing their reported cybersickness scores for the later sessions [73]. Additionally, breaks can help people recover from cybersickness symptoms but may not eliminate them [73, 76]. For instance, Gutiérrez et al. [30] and ITU-T Rec. P 919 [55] recommend taking breaks of at least 15 minutes between two consecutive viewing sessions when the session duration is more than 25 minutes. In [30], a positive effect of the break was seen, and there was no significant increase in the severity of cybersickness scores before and after the test.

3.4.3 Discussion

Different aspects of the video content and context can influence the severity of cybersickness symptoms. A high amount and speed of camera motion and moving objects induce increased cybersickness. Regarding the camera, vertical motions were shown to lead to higher cybersickness scores when compared to horizontal motions. A prominent 3D effect in video content also induces higher cybersickness scores than without the 3D effect. The recording camera position should be maintained to align with the viewer's body height or lower to minimize cybersickness effects.

Some studies showed that videos lasting 8 minutes or less did not evoke high SSQ scores. However, the severity of symptoms increased when the video duration exceeded 8 minutes [48, 82]. In 6-DOF VR, early works show that the severity of symptoms decreases after 60 – 75 minutes [11] — however, a replication of these findings might be appropriate to investigate if the easing of symptoms sets on earlier with newer, better hard- and software. To the best of our knowledge, extensively longer exposures with 360°-videos were not considered in cybersickness studies, and hence, we encourage further investigation of cybersickness with longer videos up to over 60 minutes.

Surprisingly, in our corpus, we did not find studies about the influence of other factors such as content with different levels of emotional valence and arousal in 360°-videos. Grassini and Laumann [26] summarized that high emotional content or content with highly arousing environments can lead to more discomfort in females than males. Because a single study shows this difference, further detailed studies should be conducted for VR and for 360°-video.

3.5 Experience-related Factors

3.5.1 Audiovisual Quality

Audiovisual quality refers to the overall viewer's experience encompassing audio and visual aspects of a multimedia presentation for different 360°-video sequences. For example, Singla et al. [72] compared cybersickness and audiovisual quality. They observed that there is a negative correlation between cybersickness and audiovisual quality, which is in agreement with the results obtained by Anwar et al. [70] and Singla et al. [74]. These observations also suggest an interaction effect between cybersickness and audiovisual quality when 360°-videos are watched in HMDs, which may contribute to lower quality scores.

3.5.2 Presence

Several studies have investigated the relationship between presence and cybersickness simultaneously [6, 74, 89] in 360°-videos. Weech et al. [89] reviewed 21 studies related to 360°-video, 6-DOF VR, and cybersickness. Their findings point to a negative correlation between cybersickness and presence (the more severe the cybersickness symptoms, the lower the presence). However, Singla et al. [74] could not establish a correlation between cybersickness and presence for 360°-videos. Similarly, Breves et al. [6] did not find a correlation between spatial presence and cybersickness in 360°-videos. Due to the lack of comprehensive studies and conclusive results, the relationship between cybersickness and presence remains unclear in the domain of 360°-videos.

3.5.3 Discussion

The relationship between video quality and cybersickness, as well as the relationship between visual quality and presence, have been investigated in both 360°-video and 6-DOF VR (e.g., Katsigiannis et al. [36]). The inverse relation between video quality and cybersickness was found in both domains. If visual quality is high, the SSQ scores will be lower and vice-versa (this aligns with our technical factors)

Concerning presence, Jerome et al. [33] explored the relationships between presence and cybersickness in 6-DOF VR. Their experimental results showed that cybersickness and presence are negatively correlated. On the contrary, Ling et al. [44] found that presence and cybersickness are positively correlated. Considering this and the results from the 360°-video domain, a clear relationship between presence and cybersickness can not be established and should be further investigated. By doing so, researchers may better understand both presence and cybersickness but may also potentially use techniques that increase presence to mitigate cybersickness.

4 Key Findings and Research Gaps

4.1 Systematic exploration of general human factors

Sect. 3.3 highlights a relatively strong contrast between findings gathered from 6-DOF VR and those from 360°-video. Regarding the factors investigated using both technologies, findings about age, gender, posture, or previous experience do not agree. This highlights a general lack of understanding about the effect of personal factors on cybersickness symptoms. A reason for these contrasting results could be that factors interact with each other: For 360°-video, our review highlighted a stark lack of research investigating the interdependencies between human factor variables. This agrees with the observations of MacArthur et al. [47], who also highlight this problem, focusing on gender. Here, studies are needed that go beyond traditional A/B tests and integrate more advanced analysis methods such as structural equation modelling (PLS-SEM, e.g., Palombi et al. [56], and Sagnier et al. [7]).

4.2 Systematic exploration of technical factors unique to 360°-video

Sect. 3.2 outlines the core challenges when investigating the influence of different technical parameters on cybersickness: the lack of software and hardware to systematically test them. Thus, researchers should invest into efforts to build dedicated devices to investigate technical factors (e.g., a modular VR-HMD similar to modular smartphones). Further, many software and hardware factors concerning cybersickness have not yet been investigated. For example, various adaptive tile-based streaming approaches, the influence of the video stitching quality, video compression, projection schemes, and dedicated ergonomic factors such as fan noise, or those relevant to more relaxed postures (e.g., lying down) including the form factor (e.g., battery on the back is problematic while lounging in a chair or lying down), heat dissipation, weight distribution, and display brightness. While many of these factors have been investigated with regard to other perceptual effects, cybersickness results are sparse. However, they are critical components within the 360°-video software and hardware ecosystem, capable of delivering high-quality videos but potentially inducing considerable cybersickness symptoms.

In addition to HMD-specific factors, several other technical parameters warrant investigation in the context of 360°-videos. This includes not only the technical parameters addressed in Sect. 3.2, but also the capabilities and qualities of 360°cameras, as well as the performance of applications responsible for playing back 360°-videos. Here, it will be useful to investigate and derive guidelines for these components (e.g., minimum specifications and functionality, respectively). Even a perfect HMD cannot display content optimally if the content has been recorded with a sub-optimal camera (e.g., lower-resolution cameras, low bitrate, colour level banding) and is displayed with suboptimal player implementations (e.g., slow rendering algorithm, unsuitable projection mechanism).

4.3 Duration of video sequences and temporal modeling

In Sect. 3.4, we outline the lack of research on 360°-video-focused research on exposure duration. While many of the reviewed studies use 360°-videos that are relatively short ($<$ 10 minutes) and some 6-DOF VR studies have explored very long durations ($>$ 12 hours), we believe that the sweet spot for complementing research for 360°-videos may lie between these values: Today's feature films, TV shows, and event broadcasts usually last anywhere between about 20 minutes and about 2 hours. Because it has been shown in 6-DOF VR that cybersickness scores increase and decrease with longer durations, it seems essential to adopt 360°-video to know how cybersickness behaves during longer exposures. Thus, two promising research directions should be pursued: First, performing user studies with longer content to gather data and describe the development of cybersickness. Second, developing time-dependent predictive models for cybersickness (potentially using the data from step one). Results from these research activities could then be used to, for example, dynamically apply various techniques to reduce cybersickness symptoms.

4.4 Longitudinal studies using 360°-videos

Long-term studies allow a better understanding of the influence of regular exposure during extended periods, i.e., beyond 4 weeks, to 360°-videos on cybersickness. Also, regular exposure could allow for more comfortable extended watching time, e.g., one hour or longer. One of the very few longitudinal studies of 360°-videos evaluated the influence of 360°-videos in learning during one month with 104 participants under 18 years old [64]. Their participants reported overall low levels of cybersickness and highlighted the effectiveness of 360°-videos in learning environments but with no significant advantage over traditional 2D videos regarding learning outcomes. Carrying out further longitudinal studies in different applications of 360°-video will allow the evolution of the 360°-video watching experience to carefully be followed and may provide a better understanding of the technology's limitations and potential uses.

5 Limitations

This paper provides an overview of studies investigating cybersickness in 360°-videos based on a literature review, contrasting findings with findings from 6-DOF VR. With that, we provide only an overview of available data and highlight contrasting (and agreeing) findings. The current review version does not evaluate the data quality of the included papers and only provides a high-level synthesis of the data.

6 Conclusion

Cybersickness is a prevalent problem hampering the more widespread adoption of VR. While heavily researched in 6-DOF VR, specific findings for 360°-videos are rare — although this media differs from 6-DOF VR regarding content, agency, and locomotion capabilities. This paper provides an overview of the current state-of-the-art and recent developments in cybersickness while watching 360°-videos. Based on a literature review, we derived several categories of factors that have been shown to influence cybersickness while watching 360°-videos. After grouping them into a respective set of four clusters (technical, human-related, context-and-content-factors, and experience-related factors), the different effects are analyzed based on the literature. From the analyses, we may derive a set of guidelines for these factors summarized here, namely better technical specifications, sitting of participants, shorter tasks, longer breaks, a stable recording camera, and mono-video, which all reduce symptom severity. In turn, contrarily set factors such as low video quality were shown to result in more severe symptoms.

We also outline several open research opportunities to further investigate and help reduce cybersickness in 360°-videos, namely interdependencies of intrapersonal factors; analysis of all involved components, not only the HMD and network; the influence of video duration; and longitudinal studies.

With our review and analysis, we present a comprehensive collection of findings in the research domain regarding cybersickness in 360°-videos, leading to a possible set of guidelines. Our work provides a basis and reference for future research, striving to allow developers and researchers alike to build and distribute 360°-videos with instructions that lead to low sickness and, by that, support the adoption of this medium specifically and VR in general.

References

[1] S. Ang and J. Quarles. Reduction of cybersickness in head mounted displays use: A systematic review and taxonomy of current strategies. *Frontiers in Virtual Reality*, 4, 2023.

[2] B. Arcioni, S. Palmisano, D. Apthorp, and J. Kim. Postural stability predicts the likelihood of cybersickness in active hmd-based virtual reality. *Displays*, 58:3 – 11, 2019. Special Issue: Visually Induced Motion Sensations.

[3] L. L. Arns and M. M. Cerney. The relationship between age and incidence of cybersickness among immersive environment users. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pages 267–268, 2005.

[4] F. Biocca. Will simulation sickness slow down the diffusion of virtual environment technology? *Presence: Teleoperators and Virtual Environments*, 1(3):334–343, 1992.

[5] P. Bockelman and D. Lingum. Factors of cybersickness. In *International Conference on Human-Computer Interaction*, pages 3–8. Springer, 2017.

[6] P. Breves and N. Dodel. The influence of cybersickness and the media devices' mobility on the persuasive effects of 360° commercials. *Multimedia Tools and Applications*, 80:27299 – 27322, 2021.

[7] D. L. I. T. Camille Sagnier, Emilie Loup-Escande and G. Valléry. User acceptance of virtual reality: An extended technology acceptance model. *International Journal of Human–Computer Interaction*, 36(11):993–1007, 2020.

[8] Z. Cao and R. Kopper. Real-time viewport-aware optical flow estimation in 360-degree videos for visually-induced motion sickness mitigation. In *Proceedings of the 25th Symposium on Virtual and Augmented Reality*, SVR '23, page 210–218, New York, NY, USA, 2024. Association for Computing Machinery.

[9] E. Chang, H. Kim, and B. Yoo. Virtual reality sickness: A review of causes and measurements. *International Journal of Human–Computer Interaction*, 36:1658 – 1682, 2020.

[10] S.-M. Choy, E. Cheng, R. H. Wilkinson, I. Burnett, and M. W. Austin. Quality of experience comparison of stereoscopic 3d videos in different projection devices: Flat screen, panoramic screen and virtual reality headset. *IEEE Access*, 9:9584–9594, 2021.

[11] S. V. G. Cobb, S. Nichols, A. Ramsey, and J. R. Wilson. Virtual Reality-Induced Symptoms and Effects (VRISE). *Presence: Teleoperators and Virtual Environments*, 8(2):169–186, 04 1999.

[12] S. Davis, K. Nesbitt, and E. Nalivaiko. A Systematic Review of Cybersickness. In *Proceedings of the 2014 Conference on Interactive Entertainment*, IE2014, pages 1–9, New York, NY, USA, Dec. 2014. Association for Computing Machinery.

[13] M. S. Dennison and M. D'Zmura. Cybersickness without the wobble: Experimental results speak against postural instability theory. *Applied Ergonomics*, 58:215 – 223, 2017.

[14] A. T. Dilanchian, R. Andringa, and W. R. Boot. A pilot study exploring age differences in presence, workload, and cybersickness in the experience of immersive virtual reality environments. *Frontiers in Virtual Reality*, 2, 2021.

[15] R. Dörner, W. Broll, P. Grimm, and B. Jung. *Virtual and Augmented Reality (VR/AR): Foundations and Methods of Extended Realities (XR)*. Springer, Cham, Switzerland, 2022.

[16] N. Dużmańska, P. Strojny, and A. Strojny. Can simulator sickness be avoided? a review on temporal aspects of simulator sickness. *Frontiers in Psychology*, 9, 2018.

[17] M. Elwardy, H.-J. Zepernick, Y. Hu, T. M. Chinh Chu, and V. Sundstedt. Evaluation of simulator sickness for 360-degree videos on an hmd subject to participants' experience with virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2020.

[18] C.-L. Fan, W.-C. Lo, Y.-T. Pai, and C.-H. Hsu. A survey on 360° video streaming: Acquisition, transmission, and display. *ACM Comput. Surv.*, 52(4), Aug. 2019.

[19] S. Freitag, B. Weyers, and T. W. Kuhlen. Examining Rotation Gain in CAVE-like Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics*, 22(4):1462–1471, April 2016.

[20] S. Fremerey, A. Singla, K. Meseberg, and A. Raake. Avtrack360: An open dataset and software recording people's head rotations watching 360-degree videos on an hmd. In *Proceedings of the 9th ACM Multimedia Systems Conference*, MMSys '18, pages 403–408, New York, NY, USA, 2018. ACM.

[21] P. Gamito, J. Oliveira, D. Morais, A. Baptista, N. Santos, F. Soares,

T. Saraiva, and P. Rosa. Training presence: the importance of virtual reality experience on the sense of being there. *Studies in health technology and informatics*, 154:128–133, 2010.

[22] P. Gamito, J. Oliveira, P. Santos, D. Morais, T. Saraiva, M. Pombal, and B. Mota. Presence, immersion and cybersickness assessment through a test anxiety virtual environment. *Annual Review of CyberTherapy and Telemedicine*, 6:83–90, 2008.

[23] G. Geršak, H. Lu, and J. Guna. Effect of VR technology matureness on VR sickness. *Multimedia Tools and Applications*, 79(21):14491–14507, June 2020.

[24] T. Goodge, V. Kroll, M. Vernon, P. Ventsislavova, and D. Crundall. A comparison of cybersickness symptoms across 360-degree hazard perception and hazard prediction tests for drivers. *Applied ergonomics*, 97:103549, 2021.

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

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

[27] C. Groth, J.-P. Tauscher, N. Heesen, M. Hattenbach, S. Castillo, and M. Magnor. Omnidirectional galvanic vestibular stimulation in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 28(5):2234–2244, 2022.

[28] J. Guna, G. Geršak, I. Humar, M. Krebl, M. Orel, H. Lu, and M. Pogačnik. Virtual Reality Sickness and Challenges Behind Different Technology and Content Settings. *Mobile Networks and Applications*, 25(4):1436–1445, Aug. 2020.

[29] J. Guna, G. Gersak, I. Humar, J. Song, J. Drnovsek, and M. Pogacnik. Influence of video content type on users' virtual reality sickness perception and physiological response. *Future Gener. Comput. Syst.*, 91:263–276, 2019.

[30] J. Gutiérrez, P. Pérez, M. Orduna, A. Singla, C. Cortés, P. Mazumdar, I. Viola, K. Brunnström, F. Battisti, N. Cieplińska, D. Juszka, L. Janowski, M. Leszczuk, A. Adeyemi-Ejeye, Y. Hu, Z. Chen, G. V. Wallendael, P. Lambert, C. Díaz, J. Hedlund, O. Hamsis, S. Fremerey, F. Hofmeyer, A. Raake, P. César, M. Carli, and N. García. Subjective evaluation of visual quality and simulator sickness of short 360° videos: Itu-t rec. p.919. *IEEE Transactions on Multimedia*, 24:3087–3100, 2022.

[31] H. Hagiya, S. Tanaka, Y. Otsuka, and F. Otsuka. Development of virtual reality educational clips for improving hand hygiene compliance among healthcare providers: a pilot study. *Teaching and Learning in Nursing*, 19(1):e17–e20, 2024.

[32] D. Jeong, S. Paik, Y. Noh, and K. Han. Mac: multimodal, attention-based cybersickness prediction modeling in virtual reality. *Virtual Reality*, 27(3):2315–2330, 2023.

[33] C. Jerome, R. Darnell, B. Oakley, and A. Pepe. The effects of presence and time of exposure on simulator sickness. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 49, pages 2258–2262. SAGE Publications Sage CA: Los Angeles, CA, 2005.

[34] C. Jicol, C. H. Wan, B. Doling, C. H. Illingworth, J. Yoon, C. Headey, C. Lutteroth, M. J. Proulx, K. Petrini, and E. O'Neill. Effects of emotion and agency on presence in virtual reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI '21, New York, NY, USA, 2021. Association for Computing Machinery.

[35] H. Jun, M. R. Miller, F. Herrera, B. Reeves, and J. N. Bailenson. Stimulus sampling with 360-videos: Examining head movements, arousal, presence, simulator sickness, and preference on a large sample of participants and videos. *IEEE Transactions on Affective Computing*, 13(3):1416–1425, 2022.

[36] S. Katsigiannis, R. Willis, and N. Ramzan. A qoe and simulator sickness evaluation of a smart-exercise-bike virtual reality system via user feedback and physiological signals. *IEEE Transactions on Consumer Electronics*, 65(1):119–127, 2019.

[37] R. S. Kennedy and L. H. Frank. A review of motion sickness with special reference to simulator sickness. 1986.

[38] H. G. Kim, W. J. Baddar, H.-t. Lim, H. Jeong, and Y. M. Ro. 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*, VRST '17, pages 36:1–36:7, New York, NY, USA, 2017. ACM.

[39] M. M. Knight and L. L. Arns. The relationship among age and other factors on incidence of cybersickness in immersive environment users. In *Proceedings of the 3rd Symposium on Applied Perception in Graphics and Visualization*, APGV '06, page 162, New York, NY, USA, 2006. Association for Computing Machinery.

[40] E. M. Kolasinski. *Simulator sickness in virtual environments*, volume 1027. US Army Research Institute for the Behavioral and Social Sciences, 1995.

[41] P. Kourtesis, S. Collina, L. Doumas, and S. MacPherson. Technological competence is a pre-condition for effective implementation of virtual reality head mounted displays in human neuroscience: A technological review and meta-analysis. *Frontiers in Human Neuroscience*, 13, 2019.

[42] C. La Raja, M. Carvello, R. Patti, L. Siragusa, C. Foppa, and A. Spinelli. Immersive reality for robotic surgical training: a pilot study using 3d visors for immersive view of the operating field. *Journal of Robotic Surgery*, 18(1):267, 2024.

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

[44] Y. Ling, H. T. Nefs, W.-P. Brinkman, C. Qu, and I. Heynderickx. The relationship between individual characteristics and experienced presence. *Comput. Hum. Behav.*, 29(4):1519–1530, July 2013.

[45] S. Litleskare. The relationship between postural stability and cybersickness: It's complicated - an experimental trial assessing practical implications of cybersickness etiology. *Physiology & behavior*, 236:113422, 2021.

[46] T. Luong, A. Pléchata, M. Möbus, M. Atchapero, R. Böhm, G. Makransky, and C. Holz. Demographic and behavioral correlates of cybersickness: A large lab-in-the-field study of 837 participants. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 307–316, 2022.

[47] C. MacArthur, A. Grinberg, D. Harley, and M. Hancock. 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*, CHI '21, New York, NY, USA, 2021. Association for Computing Machinery.

[48] M. Melo, J. Vasconcelos-Raposo, and M. Bessa. Presence and cybersickness in immersive content: Effects of content type, exposure time and gender. *Computers & Graphics*, 71:159–165, 2018.

[49] C. S. J. Mirabile. *Motion sickness susceptibility and behavior*. In G. H. Crampton, (Ed.) Motion and space sickness, Boca Raton, Florida, CRC Press, 1990.

[50] J. M. Mittelstädt, J. Wacker, and D. Stelling. Emotional and cognitive modulation of cybersickness: The role of pain catastrophizing and body awareness. *Human Factors*, 61(2):322–336, 2019. PMID: 30320515.

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

[52] D. Mur-Spiegl and S. Schlögl. Simulator sickness and felt presence: Comparing low-and high-end virtual reality headsets. *Proceedings of the Forschungsforum der Osterreichischen Fachhochschulen*, pages 4–5.

[53] D. Narciso, M. Bessa, M. Melo, A. Coelho, and J. Vasconcelos-Raposo. Immersive 360 video user experience: impact of different variables in the sense of presence and cybersickness. *Universal Access in the Information Society*, 18(1):77–87, 2019.

[54] A. Ozkan and U. Celikcan. The relationship between cybersickness and eye-activity in response to varying speed, scene complexity and stereoscopic vr parameters. *International Journal of Human-Computer Studies*, 176:103039, 2023.

[55] I.-T. P.919. Subjective test methodologies for 360º video on head-mounted displays. Recommendation P.919, Oct. 2020.

[56] T. Palombi, F. Galli, F. Giancamilli, M. D'Amico, F. Alivernini, L. Gallo, P. Neroni, M. Predazzi, G. De Pietro, F. Lucidi, A. Giordano, and A. Chirico. The role of sense of presence in expressing cognitive abilities in a virtual reality task: an initial validation study. *Scientific Reports*, 13(1):13396, Aug 2023.

[57] A. H.-Y. Park. Age differences in self-reported susceptibility to motion sickness. *Perceptual and Motor Skills*, 87(3_suppl):1202–1202, 1998. PMID: 10052078.

[58] A. Raake, A. Singla, R. R. R. Rao, W. Robitza, and F. Hofmeyer. Sisimo: Towards simulator sickness modeling for 360-degree videos viewed with an hmd. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2020.

[59] A. N. Ramaseri Chandra, F. El Jamiy, and H. Reza. A Systematic Survey on Cybersickness in Virtual Environments. *Computers*, 11(4):51, Apr. 2022.

[60] J. T. Reason and J. J. Brand. *Motion sickness*. London, Academic Press, 1975.

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

[62] L. Rebenitsch and C. Owen. Estimating cybersickness from virtual reality applications. *Virtual Reality*, pages 1 – 10, 2020.

[63] E. C. Regan. *Some side-effects of immersion virtual reality*. International Applied Military Psychology Symposium, 1993.

[64] C. Repetto, A. F. Di Natale, D. Villani, S. Triberti, S. Germagnoli, and G. Riva. The use of immersive 360° videos for foreign language learning: a study on usage and efficacy among high-school students. *Interactive Learning Environments*, pages 1–16, 2021.

[65] G. E. Riccio and T. A. Stoffregen. An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3(3):195–240, 1991.

[66] S. Rothe, B. Kegeles, and H. Hussmann. Camera heights in cinematic virtual reality: How viewers perceive mismatches between camera and eye height. In *Proceedings of the 2019 ACM International Conference on Interactive Experiences for TV and Online Video*, TVX '19, page 25–34, New York, NY, USA, 2019. Association for Computing Machinery.

[67] M. A. Rupp, K. L. Odette, J. Kozachuk, J. R. Michaelis, J. A. Smither, and D. S. McConnell. Investigating learning outcomes and subjective experiences in 360-degree videos. *Computers & Education*, 128:256–268, Jan. 2019.

[68] D. Saredakis, A. Szpak, B. Birckhead, H. Keage, A. Rizzo, and T. Loetscher. Factors associated with virtual reality sickness in head-mounted displays: A systematic review and meta-analysis. *Frontiers in Human Neuroscience*, 14, 2020.

[69] D. M. Shafer, C. P. Carbonara, and M. F. Korpi. Modern virtual reality technology: cybersickness, sense of presence, and gender. *Media Psychology Review*, 11(2):1, 2017.

[70] M. Shahid Anwar, J. Wang, S. Ahmad, A. Ullah, W. Khan, and Z. Fei. Evaluating the factors affecting qoe of 360-degree videos and cybersickness levels predictions in virtual reality. *Electronics*, 9(9), 2020.

[71] A. Singla, S. Fremerey, W. Robitza, P. Lebreton, and A. Raake. Comparison of subjective quality evaluation for hevc encoded omnidirectional videos at different bit-rates for uhd and fhd resolution. In *Proceedings of the on Thematic Workshops of ACM Multimedia*, 2017.

[72] A. Singla, S. Fremerey, W. Robitza, and A. Raake. Measuring and comparing qoe and simulator sickness of omnidirectional videos in different head mounted displays. In *9th International Conference on QoMEX*, pages 1–6, May 2017.

[73] A. Singla, S. Göring, A. Raake, B. Meixner, R. Koenen, and T. Buchholz. Subjective quality evaluation of tile-based streaming for omnidirectional videos. In *Proceedings of the 10th ACM Multimedia Systems Conference*, MMSys '19, pages 232–242, New York, NY, USA, 2019. ACM.

[74] A. Singla, R. R. R. Rao, S. Göring, and A. Raake. Assessing media qoe, simulator sickness and presence for omnidirectional videos with different test protocols. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 1163–1164, March 2019.

[75] A. Singla, W. Robitza, and A. Raake. Comparison of subjective quality evaluation methods for omnidirectional videos with dsis and modified acr. *Electronic Imaging*, 2018:1–6, 2018.

[76] A. Singla, W. Robitza, and A. Raake. Comparison of subjective quality test methods for omnidirectional video quality evaluation. In *2019 IEEE 21st International Workshop on Multimedia Signal Processing (MMSP)*, pages 1–6, Sept 2019.

[77] A. D. Souchet, D. Lourdeaux, A. Pagani, and L. Rebenitsch. A narrative review of immersive virtual reality's ergonomics and risks at the workplace: Cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload. *Virtual Reality*, 27(1):19–50, Mar. 2023.

[78] K. Stanney, C. Fidopiastis, and L. Foster. Virtual reality is sexist: But it does not have to be. In *Frontiers in Robotics and AI*, 2020.

[79] K. Stanney, B. D. Lawson, B. Rokers, M. Dennison, C. Fidopiastis, T. Stoffregen, S. Weech, and J. M. Fulvio. Identifying causes of and solutions for cybersickness in immersive technology: Reformulation of a research and development agenda. *International Journal of Human–Computer Interaction*, 36(19):1783–1803, 2020.

[80] K. M. Stanney and P. Hash. Locus of user-initiated control in virtual environments: Influences on cybersickness. *Presence*, 7(5):447–459, 1998.

[81] K. M. Stanney, R. S. Kennedy, and J. M. Drexler. Cybersickness is Not Simulator Sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 41(2):1138–1142, Oct. 1997.

[82] Y. Sumayli and Y. Ye. Motion sickness during roll motion: Vr hmd view versus monitor view. *Vibration*, 6(1):45–56, 2023.

[83] H. T. T. Tran, N. P. Ngoc, C. T. Pham, Y. J. Jung, and T. C. Thang. A subjective study on user perception aspects in virtual reality. *Applied Sciences*, 9(16), 2019.

[84] N. Taylor and A. Layland. Comparison study of the use of 360-degree video and non-360-degree video simulation and cybersickness symptoms in undergraduate healthcare curricula. *BMJ Simulation & Technology Enhanced Learning*, 5(3):170–173, June 2018.

[85] N. Tian, P. Lopes, and R. Boulic. A review of cybersickness in head-mounted displays: raising attention to individual susceptibility. *Virtual Reality*, 26(4):1409–1441, Dec 2022.

[86] H. T. T. Tran, N. P. Ngoc, C. T. Pham, Y. J. Jung, and T. C. Thang. A subjective study on qoe of 360 video for vr communication. In *2017 IEEE 19th International Workshop on Multimedia Signal Processing (MMSP)*, pages 1–6, Oct 2017.

[87] A. Ujkani, P. Hohnrath, R. Grundmann, and H.-C. Burmeister. Enhancing maritime navigation with mixed reality: Assessing remote pilotage concepts and technologies by in situ testing. *Journal of Marine Science and Engineering*, 12(7):1084, 2024.

[88] B. Wang, P. Rau, and L. Dong. F3-1 effects of controller and body posture on simulator sickness and visual fatigue in virtual reality. *The Japanese Journal of Ergonomics*, 53, 2017.

[89] S. Weech, S. Kenny, and M. Barnett-Cowan. Presence and cybersickness in virtual reality are negatively related: A review. In *Front. Psychol.*, 2019.

[90] F. Wu and E. Suma Rosenberg. Adaptive field-of-view restriction: Limiting optical flow to mitigate cybersickness in virtual reality. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, VRST '22, New York, NY, USA, 2022. Association for Computing Machinery.

[91] H. Yamamura, H. Baldauf, and K. Kunze. Pleasant Locomotion – Towards Reducing Cybersickness using fNIRS during Walking Events in VR. In *Adjunct Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20 Adjunct, pages 56–58, New York, NY, USA, Oct. 2020. Association for Computing Machinery.

[92] A. H. X. Yang, N. Kasabov, and Y. O. Cakmak. Machine learning methods for the study of cybersickness: a systematic review. *Brain Informatics*, 9(1):24, Oct 2022.

[93] A. Yaqoob, T. Bi, and G.-M. Muntean. A Survey on Adaptive 360° Video Streaming: Solutions, Challenges and Opportunities. *IEEE Communications Surveys & Tutorials*, 22(4):2801–2838, 2020.

[94] D. Zielasko and B. E. Riecke. Sitting vs. standing in vr: Towards a systematic classification of challenges and (dis)advantages. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 297–298, 2020.

[95] M. Zink, R. Sitaraman, and K. Nahrstedt. Scalable 360° Video Stream Delivery: Challenges, Solutions, and Opportunities. *Proceedings of the IEEE*, 107(4):639–650, Apr. 2019.