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A cybersickness review: causes, strategies, and classification methods

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Abstract

Virtual reality (VR) and head-mounted displays are continually gaining popularity in various fields such as education, military, entertainment, and health. Although such technologies provide a high sense of immersion, they can also trigger symptoms of discomfort. This condition is called cybersickness (CS) and is quite popular in recent virtual reality research. In this work we first present a review of the literature on theories of discomfort manifestations usually attributed to virtual reality environments. Following, we reviewed existing strategies aimed at minimizing CS problems and discussed how the CS measurement has been conducted based on subjective, bio-signal (or objective), and users profile data. We also describe and discuss related works that are aiming to mitigate cybersickness problems using deep and symbolic machine learning approaches. Although some works used methods to make deep learning explainable, they are not strongly affirmed by literature. For this reason in this work we argue that symbolic classifiers can be a good way to identify CS causes, once they possibilities human-readability which is crucial for analyze the machine learning decision paths. In summary, from a total of 157 observed studies, 24 were excluded. Moreover, we believe that this work facilitates researchers to identify the leading causes for most discomfort situations in virtual reality environments, associate the most recommended strategies to minimize such discomfort, and explore different ways to conduct experiments involving machine learning to overcome cybersickness.

Keywords: *virtual reality, head-mounted displays, cybersickness, causes, strategies, machine learning*

1 Introduction

The inclusion of virtual reality (VR) as a new means of entertainment is a trend for most technological systems. VR is an area of great importance for three-dimensional (3D) immersive graphics production for digital entertainment applications, serious games, and virtual training in various areas (health, military, science, etc.). Although most head-mounted displays (HMDs) are excellent immersive tools, they can cause multiple discomfort symptoms in their users, which can be associated with cybersickness (CS), primarily when used for extended periods (Laffont and Hasnain, 2017). Therefore, CS still poses one of the biggest challenges to investment in VR content production (Chen and Fragomeni, 2018).

According to Ramsey et al. (1999), approximately 80% of participants who have already experienced HMD-based VR reported discomfort sensations after only 10 minutes of the virtual environment exposure. Therefore, it is possible to say that extensive VR experiences tend to cause greater discomfort than shorter ones. However, discomfort can vary across individuals, with some people being more susceptible to discomfort than others.

In the literature, some theories on the paths and causes for visual discomfort in VR can be found (Kolasinski, 1995; LaViola Jr, 2000). Such paths point mainly to sensory conflicts between the vestibular and vision systems in humans. According to the authors, the conflict between such systems is one of the most frequent causes of discomfort in HMDs users. Jerald and Whitton (2009) associate sensory conflict with high latency in VR systems. High latency occurs when content is incorrectly displayed to users while they move wearing HMD devices. Such incorrect presentation may eventually result in user discomfort manifestations.

Unfortunately, ‘cybersickness’ remains as a common user problem that must be overcome if mass adoption is to be realized.

According to researches (Hua and Javidi, 2014; Stanney et al., 2020; Kim et al., 2021), the challenge of mitigating discomfort in VR and augmented reality systems is yet to be solved. VR experiences’ resulting discomfort can originate from three main causes: motion sickness, cybersickness, or simulator sickness. With this problem in mind, research has been recently conducted to reduce discomfort caused in VR systems (Budhiraja et al., 2017; Buhler et al., 2018).

The literature shows progress in combating the discomfort generated by HMD device use. Prior works were concerned with mitigating only one of the causes of discomfort, specifically, the lack of correct simulation of the depth of field (DoF) in VR environments (Porcino et al., 2016).

This work’s scope, despite its similar theme, goes beyond previous propositions. Its main objective, based on existing studies, is to conduct a CS causes, strategies, and machine learning approaches review. Additionally, we provide a relationship analysis between leading discomfort causes and strategies to minimize CS in virtual environments. This work is an extended and revised version of a previous published review (Porcino et al., 2020b).

2 Theoretical Background

Recent works point out that the discomfort generated by virtual environments is still not fully explored and explained in the literature (Lee et al., 2017; Hillenius, 2018). However, this work gathers all the main theories about discomfort manifestations possibly related to VR, which are described below.

- **Evolution theory** - Also known as "poison theory" (due to its resemblance to poison ingestion by the human body). This theory defends the axiom that it is crucial for the human body to detect forms of incorrect movement (e.g., equilibrium of a stationary body). When this occurs, a psychological conflict effect is generated, involving the coordination of the body's sensory systems; such conflict causes the body to enter a defense mode, which produces toxic substances in the stomach. When it occurs, the immediate body's response is the emesis (vomiting) process to remove toxins (Treisman, 1977).
- **Postural instability theory** - According to a study (Riccio and Stoffregen, 1991), all individuals are incited to devise tools with which to maintain a balanced and robust posture. Some virtual scenes may not ensure stable user posture control and may induce the maintenance of incorrect postures for long periods. Unstable and incorrect postures for extended durations can cause discomfort (Stoffregen and Smart Jr, 1998). According to Farkhatdinov et al. (2013), postural instability induces the disease of movement (motion sickness), which is also associated with an individual's behavioral profile.
- **Sensory conflict theory** - This study (the most accepted and cited theory) is based on the principle that discomfort in virtual reality environments originates from the conflict between the human visual system (Tovée et al., 1996) and human vestibular system (Hassan et al., 2013). Such a conflict occurs when an individual expects a sensory control from a sensory system but receives unexpected information from another. For example, a conflict occurs when an individual's vision system (eyes) receives movement information that differs from that received by his vestibular system. According to Reason and Brand (1975), author of one of the most cited theories on the topic of movement disease, such a malaise is a phenomenon caused by inadequate adaption arising at either the beginning or end owing to discrepancies between sensory systems.
- **Rest frames theory** - This theory assumes that the human brain has a particular model of representation for stationary and moving objects. The brain perceives the remaining picture as part of a stationary scene to which it then assigns a movement relative to the previous picture (LaViola Jr, 2000). In the real world, the background is generally considered the remaining picture. Take as an example a visual scene composed of a room and a ball. The human brain considers a ball movement in a room as being more natural than the reverse. To detect movement, the brain first chooses stationary objects (for example, the remaining frame). The movement of other objects is measured relatively against the stationary object (remaining frame). It is thus possible to assert that motion sickness is directly associated with the mental model's stability of representation of stationary or moving objects (Cao et al., 2018).
- **Eye movement theory** - This theory states that discomfort can be generated by unnatural eye movement, when the retina of the human eye attempts to stabilize a scene's image (Webb and Griffin, 2002). This conflict occurs when images move differently from the visual system's expectations (as in VR). In VR, eyes move in an unnatural way to try to stabilize the image produced in the retina, leading to discomfort symptoms (Flanagan et al., 2004). According to Jerald (2015), fixing the visual attention at a stationary point helps to reduce induced eye movement, thereby minimizing the sense of self-movement.

2.1 Human Sensory System

Recent research has continued to address the causes of VR discomfort (Garcia-Agundez et al., 2019; Kuosmanen, 2019). The idea that the human sensory and nervous systems are linked to the manifestation of these causes is strongly consolidated. For this reason, it is necessary to study how the human sensory system behaves when interacting with VR content.

Other recent work shows that vision is the most dominant sense among all human senses (Kucuker and Kilic, 2019). Through it, neurons communicate and several body muscles are activated, executing a whole chain process in the human system. In the context of VR, this reaction is observed during ocular vergence-accommodation. During accommodation, ocular variation occurs, which enables a vision focus change to keep images clearly and distinctly visualized on the retina. When the eyes spot a region of interest in the real world, the brain commands eye muscles to change their focal position and decrease focused region blurs (Wallach and Norris, 1963). At vergence, through stimuli, both eye lenses are manipulated and directed toward the region of interest. This ensures that the projected image will be correctly positioned for visualization by eye lenses. Accommodation stimuli and vergence are connected, meaning that any vergence alteration stimulates accommodation alteration, or vice versa (Denieul, 1982).

VR devices are considered unfavorable environments for the vergence-accommodation processes. First, images are displayed very close to the user's eyes, despite the fact that virtual images often simulate a greater distance compared with the actual distance from the lenses. For this reason, when a human eye looks around a simulated virtual scene, the focal distance of lenses does not vary, so neural commands signal a smaller depth than the simulated depth. Accommodation remains the same, but being connected to the vergence, it ends up inducing unnatural vergence in the human eye (Kemeny et al., 2020). Such discrepancy and artificial manipulation of the depth of field causes sensory conflict, which contributes to motion sickness (MS), visually induced motion sickness (VIMS), and CS symptoms.

2.2 Self-motion Perception and Cybersickness

This section presents a fundamental understanding of motion perception concerning motion sickness's (MS) primary distinctions and its subcategories. MS manifests itself because

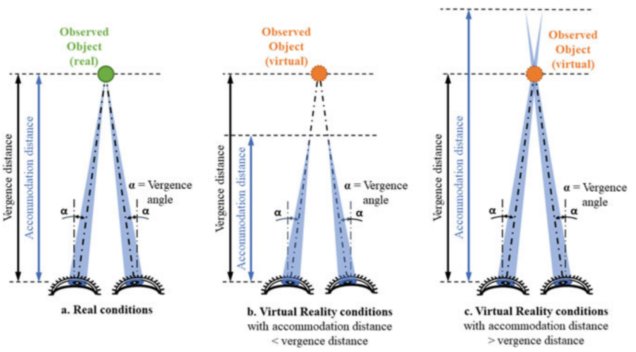

Figure 1. Kemeny's vergence-accommodation conflict example. In natural conditions (a), vergence distance and accommodation distance are the same. In VR (b and c), the vergence distance produced by HMD frequently differs from the accommodation distance (Kemeny et al., 2020).

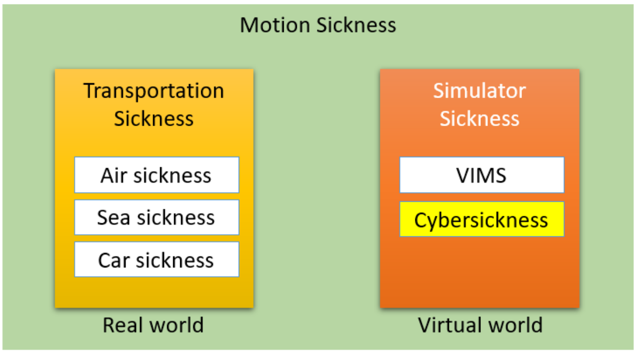

Figure 2. Motion sickness and its subcategories according to environments and trigger mechanisms.

of the information divergence emitted by the human sensory system. This occurs when there are conflicts between the sensory organs that define an individual's orientation and spatial positioning. MS is defined as the discomfort felt during a forced visual movement (without body movement), for example, airplane trips, boats, or land vehicles (Kemeny et al., 2020). Such discomfort is also experienced in virtual environments and is called VIMS.

This type of discomfort also occurs in virtual environments and is called visually induced motion sickness (VIMS). Merhi et al. Merhi et al. (2007) defined the event of VIMS during experiments with video games as a game disease (gaming sickness). Moreover, in VR, articles usually label VIMS that occurs in VR as CyberSickness (CS) (McCauley and Sharkey, 1992). In contrast, VIMS that occurs during flight or drive simulators is often called simulator sickness (Brooks et al., 2010). Overall, MS can be split into two subcategories (Kemeny et al., 2020): transportation sickness, which is tied to the real world and simulator sickness, which is associated to the virtual world and includes cybersickness (CS), as shown in Figure 2.

Cybersickness symptoms, in turn, are comparable with MS symptoms occurring in the real world such as nausea, vertigo, dizziness, and upset stomach (Howarth and Costello, 1997). CS Symptoms occur mainly with the use of VR devices, known as HMDs, such as Oculus Rift, HTC vive, among others (Rebenitsch, 2015). Kolasinski (1995) described more than 40 possible VIMS causes. These factors were grouped into three sets: simulator, task, and individual factors. Renkewitz and Alexander (2007) expanded Kolasinski's work by tabling and dividing potential factors for CS manifestations into three groups: simulator (display system), individual, and task. However, in a recent work, Rebenitsh Renkewitz and Alexander (2007) stated that many factors and configurations related to discomfort are still unknown. For example, a virtual environment may allow the user to choose the view from a first-person view perspective or the simulation of a large screen. The same applies to monoscopic rendering (an image for both eyes) or stereoscopic (an image for each eye), or even movement by accessories of VR devices (mouse, keyboard, joystick, and tracking). These examples result in an exponential number of configurations.

This work focuses on studying problems, strategies, and ways to mitigate symptoms related exclusively to CS. In other words, we delimiters this work inside symptoms that are exclusively tied to discomfort manifestation in VR environments with HMD devices.

3 Cybersickness Literature Review

Some works in the literature (Rebenitsch and Owen, 2016; Davis et al., 2014; Mousavi et al., 2013) have discussed general aspects related to CS such as current measurements of incidence of CS, ergonomic aspects, varying effects due to display and rendering mode, and usability issues. However, none of them has focused on the relationship between causes and strategies to minimize CS effects.

In this work, we are interested in answering the following research questions:

- Which are the leading CS causes reported in the literature?
- Which are the main strategies reported in the literature to minimize CS and how they are associated to causes?
- Which are the used methods to measure CS in virtual environments?
- Which the machine learning methods used to identify CS?

3.1 Methodology

Looking to answer these questions, we selected works in the literature associated with CS in four categories: causes, strategies associated to causes, CS measurements, and machine learning approaches. We conduct this research following these bibliography databases: ACM Digital Library, IEEE, SpringerLink, Google Scholar, and applying the query string below:

- (”cybersickness”) AND (”virtual reality”) OR (“review”) OR (”strategies”)
- (”cybersickness”) AND (”motion sickness”) OR (“review”) OR (”strategies”)
- (”cybersickness”) AND (”VIMS”) OR (“review”) OR (”measures”)
- (”cybersickness”) AND (”VIMS”) OR (“machine learning”)
- (”cybersickness”) AND (”deep learning”) OR (“machine learning”)

Moreover, we used the Google search engine to identify papers published by authors investigating ways to reduce motion, simulator, and cybersickness in their experiments. Besides, we considered recent English language papers published up to 4 years old for most of the included papers. In summary, we selected 157 studies. However, after a preliminary analysis, 26 were excluded. Furthermore, we did not consider publications that involved only hardware-based methodologies (i.e., eye tracking).

3.2 Causes

Several factors can cause pain and discomfort when using HMD (Porcino et al., 2017). Manifestations of CS can lead to more intense symptoms, such as nausea, eye fatigue, neuralgia, and dizziness (Kennedy et al., 1993). According to the literature (So et al., 2001; Lin et al., 2004; Draper et al., 2001; Kolasinski, 1995), it is possible to highlight the main factors that contribute to the manifestation of CS symptoms.

1. **Locomotion** - According to Rebenitsch (2015), locomotion can be correlated to CS. When the participant travels and has greater control of his movements and is close to natural movements, he will experience less CS. However, when the user experiences continuous visual movement stimulation while resting (also known as vection), it can induce painful sensations. Moreover, this problem reduces the time limit of using virtual reality in a comfortable state.
2. **Acceleration** - Visual accelerations without generating any response in the corresponding vestibular organs cause uncomfortable sensations that result in CS symptoms. High accelerations during movements produce higher degrees of CS (LaViola Jr, 2000; Stanney et al., 1997). An example of this report is considered by LaViola Jr (2000) using a virtual reality driving simulator as example. High-frequency acceleration movements contribute more to the CS. In contrast, the lower ones generate more comfortable experiences. This fact occurs because, during the acceleration increase, sensory conflicts can occur. Such conflicts make the body manifest discomfort information. However, the critical issue is the constant deceleration and acceleration. In other words, the duration of the acceleration change, not its magnitude, which makes people feel CS symptoms. An instantaneous acceleration from 0 to 100, instantaneous displacement, does not cause much discomfort than accelerations that frequently occur.
3. **Field of view** - In VR environments, a wide field of view generates a great sense of immersion. However, a wide field of view contributes to the CS manifestation. In contrast, a narrow field of view creates a more comfortable experience in VR but decrease the user's immersion (Draper et al., 2001).
4. **Depth of field** - Inadequate simulation of focus on stereoscopic HMDs with flow tracking devices creates unbelievable images and, consequently, causes discomfort. In the human eye, focus forces blur effects naturally that depend on the depth of field (DoF) and distance range of objects in the observed area. Due to ocular convergence, objects outside this range, located behind or in front of the eyes, are blurred (Porcino et al., 2017).
5. **Degree of control** - According to Stanney et al. (1997), interactions and movements that are not being controlled by the user may cause CS.
6. **Duration use time** - Many works have showed that time exposure to VR experiences might raise discomfort in a proportional way (McCauley and Sharkey, 1992; Stanney et al., 1997; Porcino et al., 2016).
7. **Latency—lag**, has persisted for years as an obstacle in the previous generations of HMDs (Olano et al., 1995). Latency is the delay between action and reaction latency is the time difference between the time of input given and the corresponding action to take place in a virtual scenario. High latency may drastically increase CS levels.
8. **Static rest frame** - The lack of a static frame of reference (static rest frame) can cause sensory conflicts and, ultimately, CS (Cao et al., 2018). According to Cao et al. (2018) most users are able to better tolerate virtual environments created by projectors such as cave automatic virtual environments (CAVEs) (Cruz-Neira et al., 1992) compared to HMDs devices.
9. **Camera rotation** - Rotations in virtual environments with HMDs increase the chances of sensory conflicts. The feeling of vection is greater in rotations when two axes are used in comparison to just one axis (Bonato et al., 2009).
10. **Postural instability** - Postural instability (Ataxia) is a postural imbalance or lack of coordination (LaViola Jr, 2000), caused when the body tries to maintain an incorrect posture due to the sensory conflict caused by the virtual environment. In other words, postural instability is the reactive response to information received by the vestibular and visual organs, which leads to CS.

3.3 Strategies Associated to Causes

In this section we describe strategies pointed out in the literature to overcome the diverse CS causes. In Table 1 is shown all strategies found in the literature with its related authors and in Table 2 is presented the association between causes and strategies identified in this study.

1. **Locomotion** Teleportation techniques help to solve the problem of locomotion in VR environments. Most VR applications use the teleportation strategy (teleporting). In teleportation, users can travel great distances by specifying the trip's destination point with the help of a marker (Langbehn et al., 2018). This technique works as follows: using a controller, the user points to the destination location and squeezes a trigger button, which immediately transports the user to the new location, also called ”pointing and teleport”. Another technique called “trigger walk” uses the concept of natural walking to reach a destination. In this case, to move around, the user uses VR control triggers instead of legs. Each control is handled by each of the user's hands in a relaxed and comfortable position (with minimum energy consumption). The user moves a step closer to the direc-

Table 1. Strategies to overcome cybersickness

Authors	Strategies
Langbehn et al. (2018)	Teleporting
Farmani (2018)	Tunneling
Sarupuri et al. (2017)	Trigger Walking
Berthoz et al. (1975) Pavard and Berthoz (1977) Bouyer et al. (2017)	Haptic Feedback
Plouzeau et al. (2018)	Changes on acceleration
Kemeny et al. (2017)	Headlock
Skopp et al. (2014)	Holosphere
Cirio et al. (2013)	Trajectory Visualization
Budhiraja et al. (2017)	Rotational blur
Carnegie and Rhee (2015) Porcino et al. (2016, 2017) Konrad et al. (2017) Padmanaban et al. (2017)	DoF Simulation
Van Waveren (2016)	Async. Time Warping for Latency
Kim et al. (2012) Sharples et al. (2008)	”Cabin” Static Frame
Kim et al. (2017)	Slowmotion
Bolas et al. (2017)	Dynamic FoV
Norouzi et al. (2018)	Dynamic Vignetting
Hillaire et al. (2008) Plouzeau et al. (2018)	Amplified Movements
Hillaire et al. (2008)	Blur Effects
Melo et al. (2018)	Time Exposure Interval
Lin et al. (2004)	Preparing the user‘s visual motion

tion indicated at each pull of the trigger (Sarupuri et al., 2017).

2. **Acceleration** According to Berthoz et al. (1975), it is possible to induce a sensation of movement using a visual response (haptic feedback). According to Pavard and Berthoz (1977), the human visual system can adapt to illusive motion but not acceleration. Various applications of VR (e.g., games and training applications) require support for haptic perception. This is because haptic perceptions can induce the sensation of acceleration in its users. When correctly applied, artificial acceleration sensation can help avoid sensory conflict. In some virtual environments (racing game), it is possible to minimize CS problems using haptic responses. Haptics is a way of transmitting physical sensations to the user, which are compatible with those captured by the user’s visual system. Bouyer et al. (2017) used haptic feedback outside a VR environment while still managing to provide users an enhanced sense of reality. According to Plouzeau et al. (2018), it is possible to measure CS acceleration using electro-dermal activity (EDA). Plouzeau et al., changed and adjusted the acceleration to visualize EDA changes. When EDA values increase, the acceleration decreases proportionately. According to research (Tran et al., 2017), the more predictable the camera movement and acceleration, the lesser the CS effects will be. The slow motion effects technique provides less sudden movements and a lower acceleration rate. This effect works best when combined with blur (image blurring), whose main goal is to return the user to a comfortable state.
3. **Field of view** The application of strategies that manipulate the FoV in commercial games is quite common. Vignette is a technique used to gradually shorten the FoV, thus reducing discomfort in VR environments (Fernandes and Feiner, 2016). A variation of this technique is the one applied in Bolas et al. (2017), where the size of the vignette and dynamic FoV are related to the camera acceleration values. Tunnel or Tunneling is also used to solve locomotion problems. Such a strategy reduces the size of the user’s FoV at the exact moment of the locomotion, thereby minimizing sensory conflict problems. Similar to the vignette, the tunnel significantly reduces the FoV. However, it is only applied during locomotion.
4. **Depth of field** Some studies include a DoF simulation agent with blur software to minimize the convergence and accommodation problems (Carnegie and Rhee, 2015; Porcino et al., 2016). The solution presented by Carnegie and Rhee (2015) pointed to the decrease of discomfort in HMD applications. Specifically, they suggested a GPU-based solution for the simulation of DoF in these applications. In an initial work, we developed a model of focus and region of interest (ROI) dynamics for visualization of objects in VR (Porcino et al., 2016). Unlike Carnegie, we used the term “dynamic” to suggest that the model moves the ROI in the 3D scene using the application. This prototype simulates a visual focus self-extraction tool, which limits the ROI in the visual field. The model uses ROI to determine DoF effects in real time, minimizing discomfort when using HMD. Additionally, we designed a methodological guide for CS minimization on VR application (Porcino et al., 2017). On the other hand, field depth simulation techniques can produce low frame rates, inducing high latency, thereby causing CS. In the work of Konrad et al. (2017) and Padmanaban et al. (2017), an approach was adopted to apply simulated DoF using an external interface, solving the problem of low frame rate. However, such a strategy is contingent on the application of specific hardware.
5. **Degree of control** Anticipating and preparing the user’s visual motion experience can reduce the problem of lack of control by user and consequently the discomfort. According to Lin et al. (2004): *“Having an avatar that foreshadows impending camera movement can help users anticipate and prepare for the visual motion, potentially improving the comfort of the experience*”.
6. **Duration use time** The study by Melo et al. (2018) relates the exposure time with discomfort manifestation and also suggests short-term or interval virtual experiences. This principle suggests that if paused periodically, VR applications could avoid CS symptoms. Consequently, the application should allow users to interrupt the experience to take a rest and then be able to return to the exactly point paused before.
7. **Latency-lag** The asynchronous time warp is a method for overcoming latency by improving a rendered

(warped) image based on the latest head-tracking data. According to Van Waveren (2016) , this method is based on augmented reality ”CamWarp” (that is applied in see-through augmented reality devices) also reduces discomfort in VR environments.

8. **Static rest frame** According to studies (Sharples et al., 2008; Kim et al., 2012), people show longer tolerance to discomfort during experiences based on VR projections (example: CAVES). One of the biggest differences between VR and projection-based systems is rest frames. In projection-based systems, the screen edges and real-world visible elements beyond the screens act as rest frames. (Bles, 1998). This raises the hypothesis that the simulation of rest frames in virtual environments can create comfortable experiences. However, adding elements to create a false rest frame that hides part of the screen may not be a good strategy for all types of VR games. It can work well for racing games, where the player is naturally inserted into a car. However, this approach may not work so well for games with first-person cameras, as they create unnatural circumstances for the player.
9. **Camera rotation** Several other works applied various techniques such as head movement amplification, whereby individual movements are amplified in VR (Kopper et al., 2011; Plouzeau et al., 2018). Another example is the blurring rotation, a technique implemented by Budhiraja et al. (2017) that uniformly applies Gaussian blurs based on the magnitude of acceleration and rotation values. There are also experiments deploying more basic techniques that lock the users' head to avoid rotational movements. According to Kemeny et al. (2017), such a strategy reduces the CS manifested during rotation by 30% compared with the use of controls to perform rotational movements. Nevertheless, the authors concluded that participants found the technique non-intuitive because it reduced the sensation of presence in the virtual environment. It is worth noting that both this technique and rotation blurring only apply to rotational movements.
10. **Postural instability** In this research, we did not find studies that reported strategies to overcome postural instability‘s CS cause. As with other forms of motion sickness, the feeling can intensify or decrease based on factors such as the length of time exposed to the instability and the magnitude of it. In the same way as our body adjusts to the postural instability on a boat, our body can also adjust to VR postural instability. As our body gradually learns how to control posture and balance in VR, symptoms of motion sickness will likely decrease (Arcioni et al., 2019).

3.4 Cybersickness Measurements

Cybersickness measuring is not trivial. The first problem is that the lack of a unique variable for discomfort level. VR users may experience multiple symptoms and some adverse effects that may not be described in the literature. Another difficulty is the considerable variation of CS susceptibility. Some users are more susceptible to CS symptoms than others. Meanwhile, research shows several ways to capture data for CS quantification. Such data can be classified as subjective, bio-signal and profile data (biological or behavioral profile).

Table 2. Strategies associated with causes (1 - Locomotion , 2 - Acceleration, 3 - Field of View, 4 - Depth Of Field, 5 - Degree of Control, 6 - Time Exposure, 7 - Latency, 8 - Static rest frame, 9- Camera's rotation, 10 - Postural Instability, 11 - Speed)

Strategies X Causes	1	2	3	4	5	6	7	8	9	10	11
Teleporting	x										
Tunneling	x								x		
Trigger Walking	x										
Haptic Feedback		x									
Changes on acceleration		x									
Headlock					x						
Holosphere	x										
Trajectory Visualization	x										
Rotational Blur	x								x		
DoF Simulation				x							
Async. Time Warping for Latency							x				
”Cabin” Static Frame								x			
Slow-motion		x							x		x
Dynamic FoV		x	x								
Dynamic Vignetting	x		x								
Amplified Movements									x		
Blur Effects	x	x	x	x					x		
Interval	x	x	x	x	x	x	x	x	x	x	x
Preparing the users̀ visual motion					x						

3.4.1 Subjective Data

The best-known way to measure CS in VR is through subjective data captured from users by applying questionnaires. Such a methodology is simple and has been historically used. However, the results can be very subjective and dependent directly on the participants' responses.

The Kennedy Questionnaire (Simulator Sickness Questionnaire - SSQ) (Kennedy et al., 1993) is the most cited tool for measuring manifestations reflecting most VR disease problems. In the SSQ, 16 symptoms of discomfort were grouped into three categories: oculomotor, disorientation, and nausea. The oculomotor assembly includes eye fatigue, trouble concentrating, blurred vision, and headache. The disorientation group comprises dizziness and vertigo. The nausea set covers upset stomach, increased salivation, and vomiting urges. When taking the questionnaire, participants classified each of the 16 symptoms on the following scale of discomfort: none (none), mild (mild), moderate (moderate), or severe (severe). The results of the SSQ are calculated and presented on four score scales: total disease (overall) and three sub-punctuations, i.e., oculomotor, disorientation, and nausea. To date, SSQ is the most widely used tool to detect symptoms of CS-associated discomfort (Carnegie and Rhee, 2015; Bruck et al., 2009).

Kim et al. (2018) revised and modified the traditional SSQ, proposing the Virtual Reality Sickness Questionnaire (VRSQ). The New VRSQ has nine items split in two classes of symptoms called “oculomotor” and “disorientation.” Some recent research (Yan et al., 2018) has adhered to VRSQ use. Sevinc and Berkman (2020) state that SSQ is not suitable for VR applications, given the psychometric quality issues. It also states as a disadvantage the fact that tests were conducted on 32 individuals only, which is an insufficient sample of all VR users.

Moreover, each individual has a different CS susceptibility level. The Motion Sickness Susceptibility Questionnaire (MSSQ) (Reason and Brand, 1975) was not created for VR but it is sometimes used in VR studies (Rebenitsch and Owen, 2016). The MSSQ can be used to determine the time taken by VR users to manifest MS symptoms in VR. This survey contains questions about the frequency with which individuals experience feelings of discomfort similar to those of MS. In MSSQ, the following scale is used: never, rarely, occasionally, and frequently. The issues are grouped into two phases of an individual's life: childhood and last "decade." This census made it possible to account for significant individual differences in MS levels.

Furthermore, the VIMSSQ-short by Golding et al. (2021) is a questionnaire to work in conjunction with the traditional MSSQ to perform a prediction of VIMS from the user. In VIMSSQ-short, the participant answers questions about the frequency of symptoms, such as nausea, headache, fatigue, dizziness, eye strain, and ways of avoiding this discomfort in different devices (e.g., video games, head-mounted displays, mobile devices). The symptoms have a score from 0 (never) to 3 (often) and a full scale from 0 to 18. Moreover, higher scores suggest a solid susceptibility for VIMS.

3.4.2 Bio-signal Data

Electrical activity of the brain is bio-signal data that often helps detect illness and behavioral body symptoms. Electroencephalography (EEG) is a monitoring methodology used to record the human brain's electrical activity. Many diseases and brain problems are diagnosed through the evaluation of such devices' data. In adults and healthy people, signs vary depending on different states, for example, awake, aware, or asleep. The characteristics of brain waves also vary according to an individual's age. Brain waves can be distinguished and separated into five different groups of frequency bands. These waves range from low to high frequencies (Sanei and Chambers, 2007).

According to studies (Morales et al., 1990; Chelen et al., 1993), it is possible to capture (delta, theta, and alpha) from certain regions of the human brain. Such regions exhibit an Motion Sickness (MS) level. Lin et al. (2007) found that 9–10 Hz values in the brain's parietal and motor regions are linked to MS levels. These values increased to 18–20 Hz in individuals exposed to MS. Other studies reported an increase in theta signal in situations similar to MS (Hu et al., 1989; Naqvi et al., 2015).

An individual's exposure to VR environments can induce stomach reactions. Studies used electrogastrogram (EGG) information to evaluate MS. According to Hu et al. (1999) and Xu et al. (1993), gastric myoelectric activities are MS indicators. Wink movements are linked to MS emergence (Dennison et al., 2016). Blinking and eye movement were observed in the work of Kim et al. (2005). Eye-tracking systems can collect information in VR environments (eye movement, pupil diameter, winks quantity, etc.) (Poole and Ball, 2006). Unnatural eye movements can contribute to CS emergence. Eye fixation can minimize the effect of discomfort (Yang X and K, 2016).

Through the body's electrodermic activity, also known as galvanic skin response (GSR), it is possible to obtain information about actions within the autonomic parasympathetic nervous system, which indicate alterations associated with cognition, emotion, and attention levels (Poh et al., 2010). Nalivaiko et al. (2014) experimented with rats that were exposed to MS triggering situations. According to the authors, thermoregulation (sweating) disturbance plays a role in the pathophysiology of nausea. Despite testing on rats, similarities with human symptoms are verifiable.

The work of Nalivaiko et al. (2014) concludes that nausea is part of the body's natural defense against poisoning and so validating the poison theory presented earlier in this review. Body cooling after "toxin" detection possibly represents a beneficial evolutionary "defensive hypothermia." This type of defensive hypothermia occurs in both humans and animals. Therefore, it is possible to conclude that visual or vestibular disorders can trigger the same type of defensive action by the human body. Studies have pointed out that the cardiac rate can significantly increase during experiments that cause MS (Kim et al., 2005).

According to Sugita et al. (2008), cardiac frequency can be considered a strong indicator of MS or CS. In VR environments, Yang et al. (2011) report that heart disease rates are even higher compared with other environments. Such cardiac elevation can induce visual discomfort (Cheung et al., 2004).

3.4.3 Profile Data

VR user profile data such as gender, age, health condition, experience, and visual fatigue are associated with manifestations of discomfort.

With respect to gender, women and men see in different ways (Abramov et al., 2012). According to Biocca (1992), women are more inclined to MS manifestations than men. According to Kolasinski (1995), this is due to a gender difference in the peripheral view. Women usually have wider FoVs than men. A wide FoV increases the likelihood of discomfort. Age is another factor that can increase CS or MS sensitivity.

According to Reason (1978), susceptibility is a product of an individual's experience as a whole and relates to MS. This theory states that older people have less susceptibility to MS than children, for example. However, studies (Park et al., 2004; Brooks et al., 2010) showed that older participants were more susceptible to MS than younger ones. According to Arns and Cerney (2005), assuming that CS follows the same pattern as MS may lead to erroneous conclusions.

Previous studies show, for example, that MS is more prevalent in younger groups. However, the study by Arns et al. demonstrated that the opposite happens in the case of CS. This difference may also be because although MS shares some similarities with CS, it does not occur in virtually simulated environments. The theory of Reason and Brand (1975) treats experience as a whole, that is, life experience (from an individual's birth to one's present). The younger the individual, the less chance one would have to be exposed to such a situation. At the time of those publications, 1975 and 1978, driving and navigating would be experiences children would not normally experience. Nowadays, however, children can be exposed to CS symptoms through VR environments.

Moreover, health conditions can contribute to increased susceptibility to MS or CS once individuals are exposed to favorable environments. According to Frank et al. (1984) and LaViola Jr (2000), any symptoms, such as stomach pain, flu, stress, hangover, headache, visual fatigue, lack of sleep, or respiratory illnesses, can lead to increased susceptibility to visual discomfort.

Furthermore, flicker is a phenomenon of visual physical discomfort. Such a phenomenon causes physical and psychic fatigue (Riva, 1997). Flicker sensitivity varies from person to person. An environment with high fps rates will possibly contribute to the user not noticing the flicker (Biocca, 1992).

Eye dominance is an important information and has been described as the inherent tendency of the human visual system to prefer scene perception from one eye over the other (Porac and Coren, 1976). According to Meng et al. (2020), the eye dominance information can be used as a guide to produce less complex VR scenes without user perception loss based on foveated rendering. An efficient render produces high fps rates. Consequently, a high fps average contributes to avoid virtual reality discomfort.

Previous exposure to MS experiences are key in terms of discomfort susceptibility (Lackner, 1990). Individuals that are more frequently exposed to MS activities (e.g., driving, playing electronics games, etc) are less susceptible to discomfort. This is most probably due to their ability to predict scenarios and situations in these environments (Guo et al., 2013).

In a previous work (Porcino et al., 2020a), we propose the Cybersickness Profile Questionnaire (CSPQ). This questionnaire considers gender, age, previous experience with virtual environments, flicker sensitivity, any pre-symptoms (such as stomach pain, flu, stress, hangover, headache, visual fatigue, lack of sleep or respiratory diseases), any vision impairments, presence of eyeglasses, posture (seated or standing) and eye dominance (Porcino et al., 2020a).

3.5 Cybersickness Classification Methods

This section presents some approaches used to classify CS in distinct virtual reality experiences, such as VR games and immersive videos.

Several studies have been conducted using deep learning models, such as convolutional neural network (CNNs) and recurrent neural networks (RNNs). Kim et al. (2019), proposed a deep learning architecture to estimate the cognitive state using brain signals and how they are related to CS levels. Their approach is based on deep learning models, such as long short-term memory (LSTM), RNN, and CNN (Lawrence et al., 1997; Graves et al., 2013; Sak et al., 2014; Islam et al., 2021)). The models learn the individual characteristics of the participants that lead to the manifestation of CS symptoms when watching a VR video or playing a VR game.

Jin et al. (2018) grouped CS causes as follows: hardware characteristics (VR device settings and features), software characteristics (content of the VR scenes), and individual user. The authors used classifiers to estimate the level of discomfort. A total of three machine learning algorithms (CNN, LSTM-RNN, and support vector regression (Drucker et al., 1997)) were used. According to the results, the LSTM-RNN obtained the best results.

Jeong et al. (2019) focused on 360° VR streaming content. They analyzed the scenarios where CS is associated with brain signals. Their work uses data from 24 individuals to discover the common characteristics of VR stream patterns associated to CS manifestation. They examined the VR content segments and observed the segments when several individuals felt discomfort at the equivalent time. However, they did not find specific and individual CS causes. Two deep learning models were used: Deep Neural Network and CNN.

Islam et al. (2021) presented an automated framework to detect cybersickness levels during a VR immersion. The framework record participants' data at specific intervals using external sensors. They used a pre-trained neural network to predict CS and adjusted the environment using with two CS reduction techniques considering the predicted level of discomfort. Moreover, Islam et al. used a deep neural network comprised of an LSTM and three densely connected layers.

In contrast, some works (Padmanaban et al., 2018; Garcia-Agundez et al., 2019) have made use of symbolic machine learning models, such as bagged decision trees (Rao and Potts, 1997), support-vector machines (Hearst et al., 1998), and k-nearest neighbors (Cost and Salzberg, 1993) to estimate and predict levels of discomfort. Padmanaban et al. (2018) designed a VR sickness predictor. In this approach, a dataset is created with some questionnaires to evaluate the physiological causes of sickness and individual historical elements to get a more precise result from users. They used the combination of two sickness questionnaires: MSSQ and SSQ, to find a single sickness value. They collected SSQ scores data from 96 participants using a set of 109 one-minute streaming stereoscopic content. Moreover, the training was performed by bagged decision tree on hand-crafted features, such as speed, direction, and depth from each video content.

Garcia-Agundez et al. (2019) aimed to classify the level of CS. The proposed model used a combination of bio-signal and game settings. User signals, such as respiratory and skin conductivity of 66 participants were collected. As a result, they mentioned a classification accuracy of 82% (SVM) for binary classification and 56% (KNN) for ternary.

Besides, Kim et al. (2019) and Jeong et al. (2019) capture data using external medical equipment. This equipment is not mainstream in terms of VR content. We focused on data captured without specific accessories. Hence, we discard the use of any external medical equipment that could harm the user experience.

Further, the above-mentioned works do not classify the CS with actual data obtained during the gameplay. In Jin et al. (2018), the best result was achieved by recurrent neural networks. This is not a surprise, as the CS is linked to the amount of exposure time and also to a time series problem. Recurrent neural networks (RNNs) show good results for time series problems. On the other hand, Padmanaban et al. (2018), and Garcia-Agundez et al. (2019) used symbolic machine learning models. However, they didn't analyze the discomfort causes and didn't focus on interactive

Table 3. A summary of related works aimed in mitigate CS problems using symbolic and deep learning models.

Authors	AI Method	Content	Cause Identification	CS Ground-truth construction
Kim et al. Kim et al. (2019)	deep learning	VR video	No	used complex physiological (e.g., EEG data)
Jim et al. Jin et al. (2018)	deep learning	VR game	No	used complex physiological (e.g., EEG data)
Jeong et al.Jeong et al. (2019)	deep learning	VR video	No	used physiological (e.g., EEG data)
Islam et al. Islam et al. (2021)	deep learning	VR game	No	used physiological data (e.g., HR, BR, HRV, GSR)
Padmanaban et al. Padmanaban et al. (2018)	symbolic machine learning models	VR video	No	designed a ranking–rating score to annotate the level of CS and compared it with the SSQ
Garcia-Agundez et al. Garcia-Agundez et al. (2019)	symbolic machine learning models	VR game	No	used physiological data (e.g. ECG) and SSQ
Porcino et al. Porcino et al. (2020a)	symbolic machine learning models	VR game	Yes	designed a cybersickness profile questionnaire (CSPQ), recorded participants' verbal feedback and compared with VRSQ responses to validate participants' CS data.

VR applications, such as VR games. However, in a previous work (Porcino et al., 2020a), we used symbolic classifiers to analyze the discomfort patterns that give more details about the neural network decisions and has a great support from literature (Džeroski, 2001; Bernardini et al., 2006; Allahyari and Lavesson, 2011). Specifically, we proposed the use of a machine learning-based approach to predict the discomfort and further analyze the decision to identify one or more causes of discomfort for each user. Moreover, our framework considered the entire VR experience: before, during, and after the participation.

In summary, most of works were focused on predicting the CS manifestation but not the causes (summarized in table 3). Predominantly, these works used deep learning models. Although recent approaches apply techniques to make deep learning models explainable (Gunning, 2017; Samek et al., 2019; Xie et al., 2020), the literature is still not strongly affirmed.

4 Considerations about CS Prediction

Although this review intends help at identifying the leading causes of discomfort and strategies to overcome CS, predicting the cause of CS is not trivial. Every user has a specific susceptibility to discomfort. Furthermore, several attributes are related to the hardware and ergonomic aspects of the devices. The literature are still far from tracing very precise causes for all specific cases.

While some of the previous work suggests that deep learning classifiers are the most suitable CS prediction (Jeong et al., 2019; Kim et al., 2019), deep neural networks are black boxes challenging to grasp on a general basis. However, recent approaches apply techniques to make deep learning models explainable (Gunning, 2017; Xie et al., 2020), but the literature is still not strongly affirmed.

On the other hand, the use of symbolic classifiers, such as decision tree or random forest, is paramount for an appropriate analysis and understanding of the decision, as opposed to deep learning methods. Furthermore, the human-readable characteristic of decision tree and random forest can help researchers to understand the discomfort manifestation reasons in VR environments, where understability is essential to highlight causes and suggest strategies to improve user experience in VR applications.

More specifically, the logical prediction path of the decision trees inherit a personal fingerprint associated to attribute weights. Usually, attributes that are closer to the tree root are more important, as they often reduce the chaos in data more than the rest (information gain, less entropy). As a general rule, the frequency in which attributes appear in the decision path is also an important piece of information. The combination of these two aspects can be a useful way to estimate the most important causes of discomfort in symbolic machine learning analysis.

Moreover, along this study we did not found any standard methodology for cybersickness data collection in terms of machine learning. Althought some works (Porcino et al., 2020a; Kim et al., 2019) collected verbal feedback or any other feedback to construct the ground truth CS data. However, verbal feedbacks are highly subjective. The same level of sickness can be different among different participants. In other words, considering a scale from 0 to 3 (none, slight, moderate, and severe), one person can consider scale 1 as slight but other, more susceptible, will fell as 3 or severe. Furthermore, collecting haptic feedback while participants are feeling discomfort often can be corrupted by delayed (i.e., cybersickness cases delays in response time), or random responses. In other words, the moment that the participant feel the pain may not the same moment which the CS cause was triggered in the participant.

In summary, there are a necessity to standardize the procedures, equipment, and materials to collect cybersickness data and the methods used to classify it.

5 Results

It is important to note that we created and conducted an iterative evaluating protocol methodology and proposed two VR games (a racing game and a flight game) using this research findings, this part of work was published in (Porcino et al., 2020a).

In summary, we elaborate on known strategies aimed at minimizing cybersickness, splitting the causes into 10 categories: locomotion, acceleration, field of view (FoV), depth of field, rotational movements, exposure time, static rest frames, postural instability, latency lag, and degree of control. Our review facilitates researchers to identify the leading causes for most discomfort situations in virtual reality environments and associate the most recommended strategies to minimize such discomfort. Furthermore, from 157 studies, we excluded 24 that were authors not aim to minimize cybersickness.

6 Final Comments and Future Work

This work investigates the causes and solutions to overcome CS while describing each current methodology. This work examined different methods to evaluate and identify discomfort situations caused by subjective, biological, and profile factors.

On the literature side, this research contributes as a bibliographic collection, describing the main causes of discomfort in VR systems while outlining strategies to minimize discomfort caused by HMDs. Thus far, we produce an cause and strategies association that summarizes this study (Table 2).

Moreover, we presented some approaches used to classify levels of CS in different VR experiences, such as 360-degree videos and VR games. Although recent works used methods to make deep learning explainable, they are not strongly affirmed by literature.

To the best of our knowledge, none work used deep learning to identify CS causes so far. However, we believe symbolic classifiers, such as decision tree can be a good way to explore and analyze the discomfort patterns in a machine learning decision considering their human-readability which is essential for analyze and identify CS causes in machine decision path.

As next steps we aim to construct a machine-learning-based solution capable of detecting discomfort situations and automatically suggesting one or more strategies to mitigate CS through the identification of causes. Firsts results regarding the discomfort analysis and prediction solution was published in a recent work (Porcino et al., 2020a).

Another straightforward way is to explore the gender differences tied to games and virtual reality tasks. Some works (Liang et al., 2019; Grassini and Laumann, 2020; Curry et al., 2020) pointed out that specific tasks can produce different results of discomfort for different user profiles and groups, regarding and not limited to: gender, age, or health issues.

Moreover, it is necessary to perform a detailed research focused on strategies, acknowledging how strategies can vary in different VR applications. An example of applying this idea is an automatic recommendation software to suggest strategies to mitigate cybersickness problems in various VR applications. A complete recommendation software might be a crucial tool for VR game designers and the VR content production industry. This tool may optimize the VR production line, reducing the production time and the decision-making process from the game designer's team.

We believe that all the aspects discussed in this study should be considered while dealing with automatic and intelligent approaches for CS analysis and prediction. Finally, this work can be a start point to elaborate more accurate game design techniques for VR games and applications.

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